Transgressive Development of Coal-bearing Coastal Plain to Shallow Marine Setting in a Flexural Compressional Basin, Paleocene, Svalbard, Arctic Norway

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ABSTRACT

The most extensive Paleogene succession on Svalbard, in the Arctic north of Norway, is found in the Central Tertiary Basin of Spitsbergen. It consists of a clastic basin fill of mudstone, sandstone, coal and rare conglomerate beds. A coastal plain to shallow marine setting is suggested for the Late Paleocene Firkanten Formation, the lowermost unit of the Paleogene succession. This is the first comprehensive facies model, sequence stratigraphic analysis, and paleogeographic reconstruction of the Firkanten Formation, based on new borehole cores and field data.

The facies analysis reveals that sedimentation occurred in a flat relief coastal plain environment with tidal, wave, and storm influence but only minor fluvial sediment input. Previous interpretations have described the Todalen Member, the lower part of the Firkanten Formation as delta plain deposits. The detailed sequence stratigraphic analysis and paleogeographic reconstruction show that the Firkanten Formation consists of parasequences combined into parasequence sets bounded by major flooding surfaces. The succession is dominated by aggradation in a step-wise transgressive setting. The general tectonic subsidence was at all times greater than any eustatic sea level fall since there are no relative sea level falls detected in the succession. The basin was formed as a depression in front of the West Spitsbergen Fold and Thrust Belt.

Thick sections of coastal plain deposits of coal, carbonaceous shale, and other fine grained clastic sediments were deposited on the coastal plain, in mires and swamps that graded into tidally influenced lagoons. The coastal plain was protected from wave reworking by sandy barrier bars but was flooded during periods of increased relative sea level rise probably from eustatic sea level rise. The foreshore and shoreface deposits are characterised by fine grained sandstone and a few pebbly beds, making up the Endalen Member, the upper part of the Firkanten Formation. The foreshore was characterised by sandy barrier bars of long shore transported fine grained sandstone. The foreshore and shoreface show a high degree of wave

and storm influence. Alluvial fan deltas built out from the thrust front, transporting coarse grained material to the basin. The base of the Paleocene succession is made up by the unconformity to the Lower Cretaceous Carolinefjellet Formation, representing the lower sequence boundary characterised by poorly sorted sediment of re-deposited weathered material and vegetation.

Large, newly discovered footprints of the Pantodont '*Titanoides*' from the Todalen Member coal layers are the earliest evidence of a large mammal on Svalbard and the northernmost discovery from the Paleocene. The traces are named *Thulitheripus svalbardii* Ign nov. isp. nov. Large Paleocene Pantodonts are previously only known from North America and their presence on Svalbard, confirms the postulated DeGeer route for migration of mammals in the Late Paleocene to Eocene.

The Central Tertiary Basin is interpreted as being of flexural origin, formed as a result of crustal shortening in West Spitsbergen due to convergence with Greenland related to the opening of the Northern Atlantic in the early Paleogene. The Late Paleozoic clasts in conglomerate beds provide evidence that there was uplift and erosion of at least 2000 m of rocks in the West Spitsbergen Fold and Thrust Belt, directly adjacent to the western margin of the basin. The sand came from Mesozoic strata uplifted to the north and northwest of the basin. The deformation zone is relatively narrow and the strata are folded to vertical on the western side of the basin. The Central Tertiary Basin shows very little deformation. It is suggested that the most important factor creating the Central Tertiary Basin was compressional folding and not extension or foreland basin flexural loading as has been postulated previously, in accordance with initial continental and shallow marine basin deposits. The compressional folding model suggests that the orogeny did not necessarily create an extensively elevated mountain belt. The footprints suggest that there was no obstruction for migrating Pantodonts such as a seaway or mountain range between Svalbard and Greenland/Ellesmere Island in the Late Paleocene.

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I would like to thank Dr. Gary Nichols, my head supervisor, for help and support during this project and without whom this work would have been very different indeed. I immensely enjoyed all the interesting discussions and it was always fun to work together with the project. Your interest in the project and critical reviews improved the results. I would also like to thank everyone at the Department of Earth Sciences at RHUL for letting me be part of the inspiring and enjoyable environment.

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I would like to thank all the good friends, I got to know during this period who has supported me to keep going. Finally the greatest thanks go to my husband for all encouragement, help, and critical reviews he has given me. Your confidence in me was the best support.

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1. INTRODUCTION

In this chapter the aim and the hypothesis of this project are introduced as well as the outline of the thesis. The current status of the articles produced during the project is stated. The material used in the research and the methodology are presented.

1.1 Aim of the re-investigation of the Firkanten Formation

The Firkanten Formation of Paleogene on Svalbard, Arctic Norway represents the first sediments deposited in the Central Tertiary Basin. The coal-bearing strata have been in focus for more than a hundred years within the mining industry. Nonetheless, there has previously not been made any comprehensive investigations considering the sedimentary depositional environment and coal generation in the context of basin development and sequence stratigraphic development.

A new extensive core material (drilled by SNSK since 2002 and still ongoing) provided an opportunity to do a detailed investigation of the Firkanten Formation based on modern sedimentary analysing methods. The aim of the project was to re-investigate the depositional environment in a sequence stratigraphic view to get the paleogeographical development through time. The results were evaluated in context of basin formation to get a better understanding of the regional tectonic model. The purpose was to create a comprehensive model of the depositional environment, the development of the basin, and the understanding of the formation of the basin and the depositional system. In addition the objective was to be able to make better predictions for future coal exploration.

The hypothesis was that inconsistencies in the previous interpretation had lead to incorrect conclusions. Therefore, it was important to build a comprehensive model for the basin as a whole, to be able to create a more consistent interpretation.

1.2 Outline of thesis

The research results that came out of this project are presented in four articles submitted for publication in different international journals. This thesis is based on these articles with an extended introduction of the subject and a comprehensive conclusion that summaries the result of the entire work. The outline of the thesis is presented below.

1. Chapter 1 consists of a general introduction to the material and specific methods used in the investigation.

2. It is followed by background knowledge of the Paleogene sedimentary deposits of Svalbard in Chapter 2, stating the understanding of the Firkanten Formation prior to this work. In Chapter 2 a general introduction to coastal depositional environments, coal generation and flexural basins is also found. Questions raised regarding inconsistencies in the previous interpretations are also presented in this chapter.
3. Chapter 3 provides a synopsis of the research, further presented in detail in the articles and summarises the conclusions. The questions raised in Chapter 2 are addressed and briefly discussed.

In Chapters 4 to 7 the four articles generated from the results of this work are presented.

4. Chapter 4 focuses on the interpretation of the depositional environment from facies analysis.
5. Chapter 5 addresses the sequence stratigraphic interpretation and the paleogeographic reconstruction, which puts the results from the facies analysis into lateral distribution and development through time.
6. Chapter 6 presents the results from the regional investigation of the basin discussing the formation of the Central Tertiary Basin.
7. In December 2006 large footprints were found in the mine outside Longyearbyen. The footprints showed to be of Pantodonts and are described in Chapter 7.

8. The results are summarised in Chapter 8 with a conclusion of the new information and knowledge that has come out of this research project. The answers to the questions raised in Chapter 2 are summarised. Limitations and suggested work for the future are also discussed.
9. This chapter contains the references used in the thesis except for the ones in the articles (Chapters 4-7), which are listed in each article respectively.
10. In this chapter the content of the Appendix, which is found on the attached CD is listed. The Appendix contains additional material such as pictures of facies and logs as well as large scale images of some of the figures in the thesis and the articles. There are also pdf versions of the articles in their submitted format.

1.3 List of articles and contributions

The contributions by the listed authors to each manuscript are summarised below:

Chapter 4: Article 1

Lüthje, C. and Nichols, G. *Submitted*. Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. Sedimentology.

C. Lüthje: principal investigator and author

G. Nichols: discussions and manuscript review

Contribution by C. Lüthje: 90%

Chapter 5: Article 2

Lüthje, C. and Nichols, G. *Submitted*. Transgressive coastal plain to shallow marine development of the Paleocene strata of Spitsbergen, Arctic Norway. Journal of Sedimentary Research.

C. Lüthje: principal investigator and author

G. Nichols: discussions and manuscript review

Contribution by C. Lüthje: 90%

Chapter 6: Article 3

Nichols, G. and Lüthje, C. *Submitted*. Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. Basin Research.

G. Nichols: principal investigator and co-author

C. Lüthje: principal investigator, co-author, and discussions

Contribution by C. Lüthje: 70%

Chapter 7: Article 4

Lüthje, C., Milàn, J. and Hurum, J. *Submitted*. Paleocene tracks of the mammal Pantodont genus *Titanoides* in coal-bearing strata, Svalbard, Arctic Norway. Proceedings of the Royal Society B.

C. Lüthje: field investigation, sedimentological principal investigator and co-author

J. Milàn: paleontological principal investigator and co-author

J. Hurum: field investigation, identification, and discussions

Contribution by C. Lüthje: 70%

1.4 Material and study area

Coal has always been the most important natural resource on Svalbard. All settlements on Svalbard (Barentsburg, Longyearbyen, Pyramiden, Svea, and Ny Ålesund) originate from coal mining and all on Paleogene coal except Pyramiden, which was based on mining of Carboniferous coal. Industrial coal mining started in the beginning of the 20th century and is still the main industry followed by tourism and scientific research. The main Norwegian settlement, Longyearbyen (Fig. 1.1), is dependent on coal for all power use and heating. The largest part of the coal is exported to the power industry but since the quality of the coal is excellent some is used in steel production.

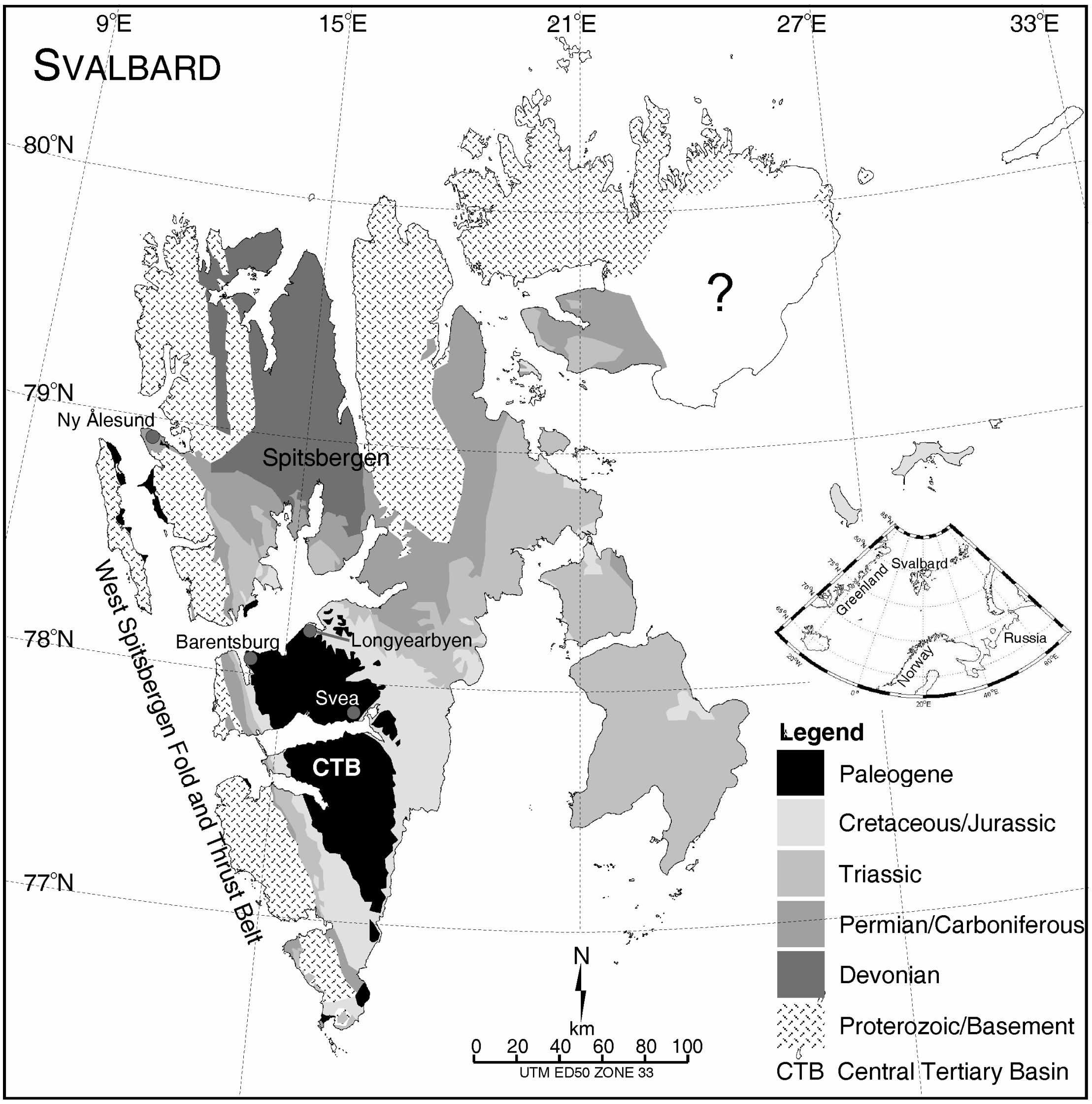

Fig. 1.1 A simplified geological map of Svalbard. The Central Tertiary basin occupies the centre of the southern part of the main island, Spitsbergen, after (Dallmann, 1999).

The study area was the coal-bearing Firkanten Formation of Paleogene in the Central Tertiary Basin (Fig. 1.1). There is a small section of Paleogene deposits in Ny Ålesund; the Ny Ålesund Subgroup that is similar in age and appearance to the Firkanten Formation. In addition there are two local basins of younger Paleogene deposits; the Buchananisen Group in Prins Karls Forland and the Calypsostranda Group at Skilvika/Renarodden. The Buchananisen and Calypsostrand Groups are younger sediments (suggested Late Eocene – Oligocene) than the Paleocene Firkanten Formation (Dallmann, 1999). The deposits are much coarser and the two sections are interpreted as being deposited in localised basins in the West Spitsbergen fault zone not related to the Central Tertiary Basin (Steel et al., 1985; Dallmann, 1999) and they were therefore not considered in this study. The Ny Ålesund Paleogene strata are presently being investigated by the author in context of being a northern extension of the Central Tertiary Basin. However, since this is an ongoing investigation where the results are depending on fieldwork in 2008 it is not presented here.

The material used in this study was mainly the new cores and field observations. Due to inaccessibility to some remote areas on Svalbard, data from reference material were also used to get a better spatial coverage of the entire basin (Fig. 1.2). However, the quality of data from the different sources varies greatly.

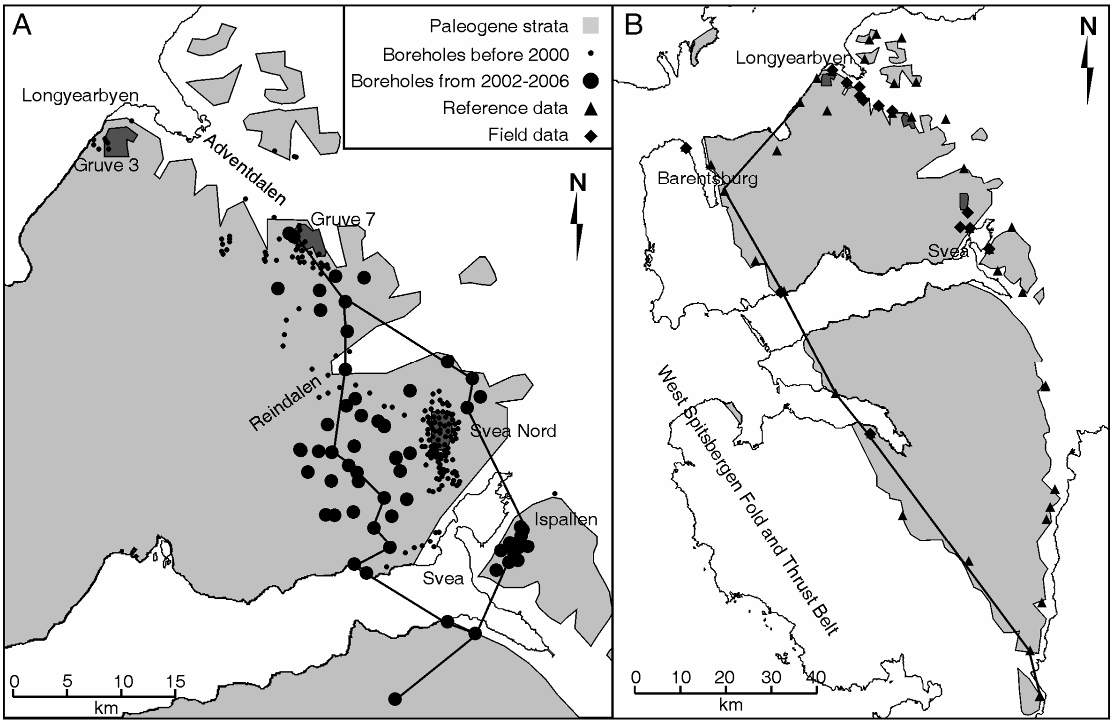

Fig. 1.2 Detail of Figure 1.1 showing locations of settlements, mines, boreholes, and field locations. Field data is separated into own field observations and references. The main concentration of boreholes is in the eastern part of the basin. Outlined are the cross sections of the correlations presented in Article 2 in Chapter 5 and also found in Appendix 4.3.

Core data

The Norwegian coal mining company SNSK "Store Norske Spitsbergen Kulkompanie" has drilled and cored since 2002 in the north eastern part of the Central Tertiary Basin between Longyearbyen and Svea for coal exploration (Fig. 1.2). The good coverage of boreholes and the excellent quality of the cores in this area made it possible to do a detailed study. There are about 60 cores available from 2002-2006 but not all penetrated the Firkanten Formation. Unfortunately most of the older cores (predating 2002) are almost completely lost today, which also includes cores from Ny Ålesund and Russian/Soviet explorations.

The new cores were logged with a focus on the Todalen Member, the Endalen Member and the lowermost part of the Basilika Formation, at scale 1:20 and have been rescaled to 1:50 and 1:200 using SedLog (www.sedlog.com). Corelogs are presented in Appendix 2.1. Cores were picked to provide good spatial distribution and good examples of the Todalen Member. Only cores penetrating the underlying Carolinefjellet Formation were considered initially. The facies scheme is based on observations in these cores.

Overview (5 x 1 m core/picture) and detailed digital pictures (~3000, some presented in Appendix 1.1 and 4.1) were taken during logging, providing a good references material for the facies analysis. Three of the cores were sampled for thin sections (70 slides, some presented in Appendix 3.1) for mineralogical analysis. The core diameter is about 4 cm and since they are not cut, all investigations were made on round surfaces.

Field data

The Firkanten Formation outcrop exposures are of various qualities and the fine grained Todalen Member is especially poor. However, field observations provided a better understanding of the spatial distribution of the facies identified from cores. Pictures of facies from field are presented in Appendix 1.2 and 4.1. Fieldwork was carried out in September 2004, July-August 2005 and August-September 2006 in the Longyearbyen and Svea areas. Numerous logs were made but due to poor exposures only 3 complete sections of the Todalen Member were possible to log. 29 samples were collected for mineralogical analysis and additional studies. During fieldwork old logs from references were re-evaluated.

Mine data

Three continuous coal sections were sampled and logged in the mines; Svea Nord, Gruve 7, and Gruve 3 (Fig. 1.2, pictures in Appendix 3.2). The samples were taken for detailed coal analysis such as microstratigraphy, vitrinite reflectance, palynology, and paleoclimate studies using stable isotope analysis. Sampling a second section through the mine Svea North was scheduled to August 2006, but had to be cancelled due to the mine fire.

These samples (45 pieces) were cut and slabs were prepared at Royal Holloway University of London. The samples were scanned using a high resolution flatbed scanner giving a good overview of the initial coal analysis. The coal slabs are currently being analysed at University of Liverpool. The initial results show some variations in maceral content through the seam and some marine brackish influence (pyrite presence).

Coal and geochemistry data

SNSK sample all coal in the cores for geochemistry (ash or siliciclastic material, sulphur, and phosphor) and occasionally maceral content. The coal was analysed in bulk samples of 20 cm. The existing geochemistry data from earlier exploration cores (predating 2002) was merged with geochemistry analysis from new cores. Some of the old data from the 1970's do not have geographic location information but only notes about the collection area. In the newer sample set it was possible to get trends within the coal seams from the geochemical data. Coal samples from before 2002 was also analysed for different elements. The available data is as following:

- Ash, sulphur, phosphor, 43 elements (Al, Si, P, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Ru, Rh, Pd, Ag, Cd, Sn, Sb, I, Ba, La, Hg, Pb, Ra, Th, U, and Pu), and coal maceral (300 samples) from borehole and field samples without location, from the 1970's
- Thickness of the main coal seam, ash, sulphur, and phosphor content (886 samples; 125 of boreholes) with uncertain locations from the 1980's and 1990's
- Records of the depth of the top and the base of the coal-bearing layers (125 samples) with uncertain geographical locations, from boreholes mainly from the 1980's and 1990's
- Records of the depth of the top and the base of the coal-bearing layers with geographical locations (73 samples complete, 147 of the coal thickness) from the 1990's and 2000's
- Records of depth of stratigraphic boundaries and coal layers (28 samples) from boreholes with geographical data, from the 2000's
- Thickness of the main coal seam, ash, sulphur, and phosphor content (34 boreholes), displaying trends within the coal seam, with geographical location, from the 2000's

- Maceral data for 6 boreholes from the 2000's

Since this material belongs to SNSK and is confidential only the results of the analysis are presented. The material was statistically examined but the results showed that the data often was inadequate to be used for further interpretations. The specific coal seam of the samples had not always been registered and the location was often missing. However, distribution of ash, sulphur, and phosphor together with the maceral content were found to be useful in the analysis of the newer samples where depth and location of each sample were recorded. Discrepancy between the different coal seams based on the geochemistry was possible, which is also indicated by throughout geochemical analysis combined with maceral study (Orheim et al., 2007).

Reference data

To get a denser data set especially from remote areas, data from references were re-evaluated. Sedimentological logs from references from areas where field work was carried out were re-evaluated in field, according to the new facies scheme created from the boreholes. Some re-drawn logs are presented in Appendix 2.2.

The records of the early sedimentological investigations of the Firkanten Formation are mainly unpublished theses and reports from SNSK e.g. (Kalgraff, 1978; Steel and Dalland, 1978; Dalland, 1979; Ytreland, 1980; Tønseth, 1981; Hansen, 1982; Nøttvedt, 1982; Bruhn, 1999; Wilhelmsson, 1999; Hansen, 2004; Jochmann, 2004; Kostro, 2005). In addition there are some published papers and books e.g. (Kellogg, 1975; Steel et al., 1981; Steel and Worsley, 1984; Steel et al., 1985; Müller and Spielhagen, 1990; Michelsen and Khorasani, 1991; Nøttvedt et al., 1992; Harland, 1997; Bruhn and Steel, 2003; Cmiel and Fabianska, 2004; Nagy, 2005) and a collection of reports from the Norwegian Polar Institute e.g. (Nagy, 1966; Vonderbank, 1970; Harland, 1995). There are also reports for the different geological maps of Svalbard e.g. (Hjelle et al., 1986; Winsnes, 1988; Salvigsen et al., 1989; Dallmann et al., 1990; Dallmann et al., 1994; Major et al., 2001) whereof the data are compiled in (Dallmann, 1999). Logs, when available from these references were used in the analysis and re-evaluated in context of the new interpretation.

Even if the Firkanten Formation has been of interest for a long time due to the coal this is the first comprehensive facies and sequences stratigraphic investigation also considering paleogeography and regional tectonic basin development.

1.5 Methodology

The object of this project was to investigate the sedimentary strata of the Firkanten Formation in perspective of the paleogeography and depositional environment. A sequence stratigraphic approach was taken to analyse the spatial distribution through time of the different depositional environments. To be able to do this, it was required to make a facies analysis first.

Facies analysis

The facies were originally defined from the core logs. The 44 subfacies were defined from the sedimentary appearance based on lithology, grain size, colour, lamination, structures, heterogeneity, prominent features, occurrence of clasts, organic material, root structures, bioturbation, layer boundary, thickness distribution, associated facies, and occurrence in the stratigraphy. Furthermore the subfacies were related to field observations.

The 44 subfacies were combined into 10 facies that were defined from core and field data and thereafter interpreted to a specific depositional environment. Each of the facies was identified with the same criteria as the subfacies. The facies data is presented in Appendix 1.3 and 4.1.

The facies were further combined into facies associations representing general depositional environmental zones. The facies associations were based on the facies but identified with help of modern analogues. The analogues were chosen on the similarity to the facies assembly and other background knowledge such as climate and relative sea level change. The depositional environment model is found in Appendix 4.2.

Sequence stratigraphic analysis

Vertical trends in sedimentary strata were identified from the facies analysis and further used in the sequence stratigraphic analysis. In general, sequence stratigraphic analysis is the basis for the correlation and understanding of horizontal relationship and thereby the lateral distribution of facies through time. This can, for example give a better understanding in predicting the occurrence of coal in subsurface. Coal-bearing deposits represent environments that are prone to react to very small changes in base level and are therefore excellent for sequence stratigraphic interpretations.

Three dimensional sedimentary models and correct stratigraphic relationships can only be obtained by sequence stratigraphic interpretation. Correlation of different environments by horizontal bounding surfaces is essential to make paleogeographic reconstructions. The correlation of the Firkanten Formation was greatly revised, since previous correlations were based on lithostratigraphic models. This new sequence stratigraphic interpretation displays the reality better, as it is seen in the mines and outcrops and also compared to modern analogues. The modern analogues provided useful scale for the extension of different zones in the depositional system but also angle of the coastal plain. However, different maximum and minimum scales and angles were considered.

The sequence stratigraphic model is presented in Chapter 5 and correlation panels are in Appendix 4.3. The method to create the correlation was based on the result from the facies analysis combined with modern analogues. Surfaces representing base level change were identified from the facies distribution, such as major flooding surfaces. Nearby logs were initially correlated and then the correlation was propagated further away. The base of the Paleocene could not be used as a datum line since it is characterised by local topography. However, the coal layers showed to be useful marker horizons. The vertical sections were not de-compacted since assumptions of, for example the compaction rate and burial depth would have been necessary to make and this would have added more uncertainties.

Paleogeographic reconstruction

The result of the facies analysis indicated the type of depositional environment that the Firkanten Formation represents. The sequence stratigraphic analysis showed the lateral development through time. By combining the results of the two analyses and evaluate it in perspective to the modern analogues, paleogeographic maps were constructed (Appendix 4.4). The paleomaps gives a better visualisation of the interpretation but also verify the sequence stratigraphy. Anomalies indicated the need for ratification of the sequence stratigraphic interpretation.

2. BACKGROUND

In this chapter general background knowledge and previous interpretations of the Paleogene strata of Spitsbergen is presented. Former models are discussed and questions to the current interpretations are raised. A general introduction to coal generation in coastal depositional areas and formation of flexural basins is also found.

Svalbard has for a long time been an area of sedimentary deposition with only one major hiatus from Albian/Aptian to Paleocene. The succession includes an almost continues section from post-Caledonian Devonian red sandstones, found in the north, to Paleogene of the central area (Figs 1.1 and 2.1) (Steel and Worsley, 1984; Dallmann, 1999). A more complete description of the stratigraphic record on Svalbard is presented in details in Chapter 6 (Nichols and Lüthje, Submitted). The youngest Mesozoic strata exposed on Svalbard of Aptian/Albian age is the Carolinefjellet Formation underlying the Firkanten Formation (Fig. 2.2) (Dallmann, 1999). It is a succession of mudstone and fine sandstone deposited in an open shelf environment. In the Cretaceous, Svalbard was on the margin of the Barents Shelf lying adjacent to the northern edge of Greenland and Ellesmere Island (Fig. 2.3). The whole area had been relatively stable continental crust since the Carboniferous (Harland, 1997). In the Cretaceous, however, oceanic areas started to open to the north in the Arctic Ocean and also to the south in the Northern Atlantic. Svalbard was uplifted and eroded, creating the pre-Cenozoic hiatus (Blythe and Kleinspehn, 1998). Later in the Paleocene, tectonic plate movements lead to the creation of the West Spitsbergen Fold and Thrust Belt and the Central Tertiary Basin (Figs 1.1 and 2.4). Rifting and ocean floor spreading between Svalbard and Greenland is dated from Oligocene (Blythe and Kleinspehn, 1998).

2.1 Paleogene setting of Svalbard

The Paleogene strata of the Van Mijenfjorden Group (Fig. 2.2) on Svalbard are mainly found in the Central Tertiary Basin that covers most of the southern half of the main island Spitsbergen (Fig. 1.1). The Paleogene the Buchananisen and Calypsostranda Groups are interpreted as not connected to the Central Tertiary Basin but deposited as local basins (Steel et al., 1985; Manum and Throndsen, 1986; Dallmann, 1999). These sections will therefore not be discussed here.

The Paleogene Ny Ålesund Subgroup is being investigated as a possible northern extension of the Van Mijenfjorden Group. Based on a sequence stratigraphic concept rather than lithostratigraphy the Firkanten and Basilika Formations are related in time. Following the

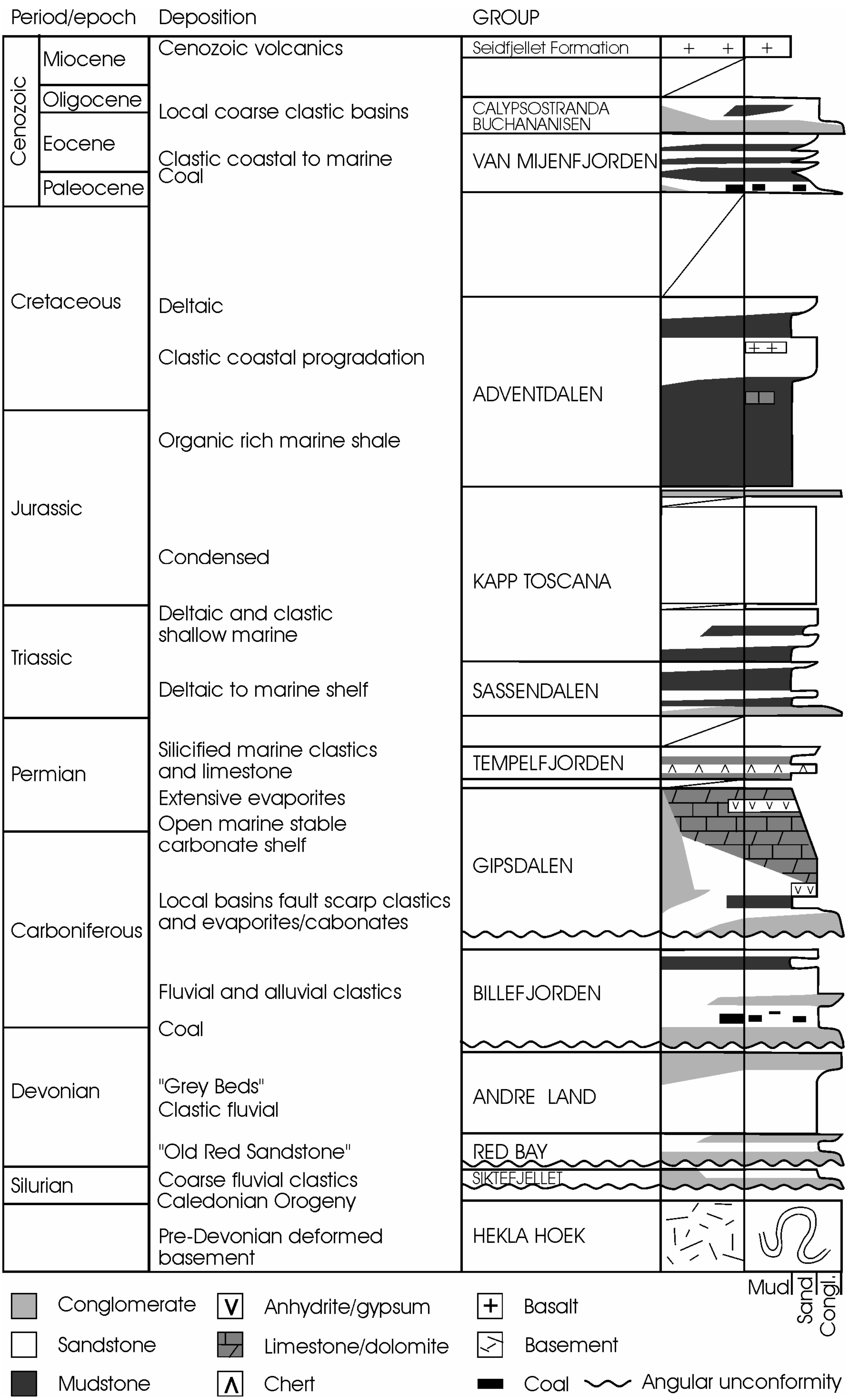

Fig. 2.1 The stratigraphy of the sedimentary record of Svalbard, from (Nichols and Lüthje, Submitted) based on (Worsley et al., 1986; Dallmann 1999).

same concept Ny Ålesund coal-bearing strata could then be related to marine deposits further south. It has been suggested previously that the Ny Ålesund Subgroup is the last extension of a northwards back stepping system (Midbøe, 1985; Steel et al., 1985). The result of this ongoing investigation will not be discussed further.

Van Mijenfjorden Group

The Firkanten Formation is the earliest deposits in the Central Tertiary Basin (Fig. 2.2). The Todalen Member consists mainly of fine grained muddy deposits, mudstones, muddy sandstone and coal, as well as occasional pebbles or mudclasts conglomerate. The Endalen Member is characterised by fine grained well sorted sandstone that is often bioturbated, and rare pebbles. The Basilika Formation consists of muddy sandstone to silty mudstone with intense bioturbation.

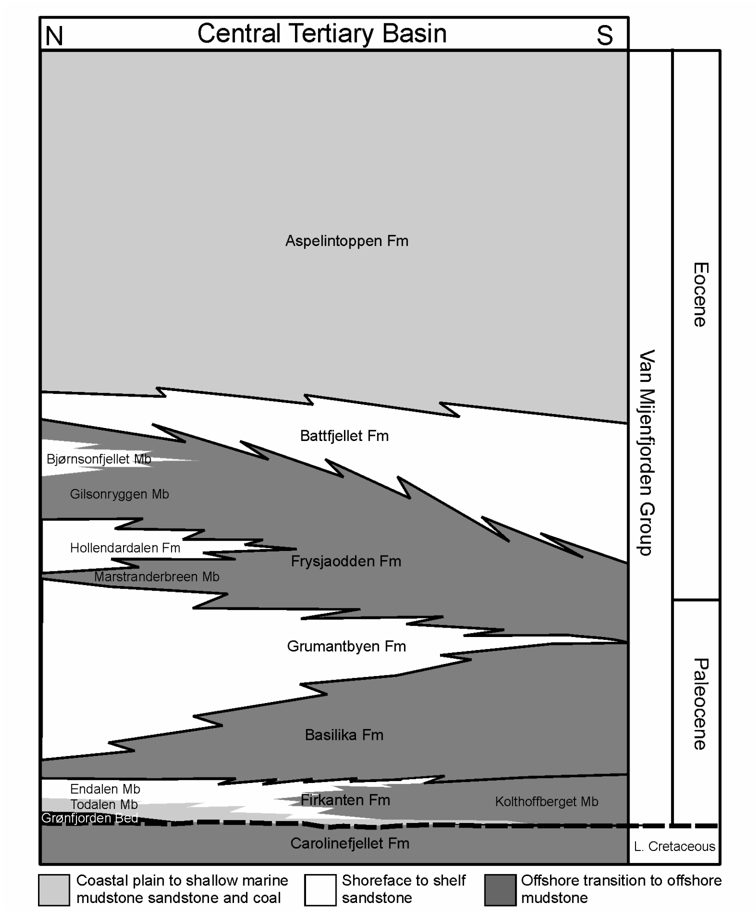

Fig. 2.2 The stratigraphy of the Paleogene Van Mijenfjorden Group in the Central Tertiary Basin of Spitsbergen. The focus of this study is on the lower part of the succession, the Todalen and Endalen Members of the Firkanten Formation, from (Lüthje and Nichols, Submitted a), based partly on (Steel et al., 1985; Bruhn and Steel, 2003). Geometries are based on relative thickness variations (Dallmann, 1999) over the basin.

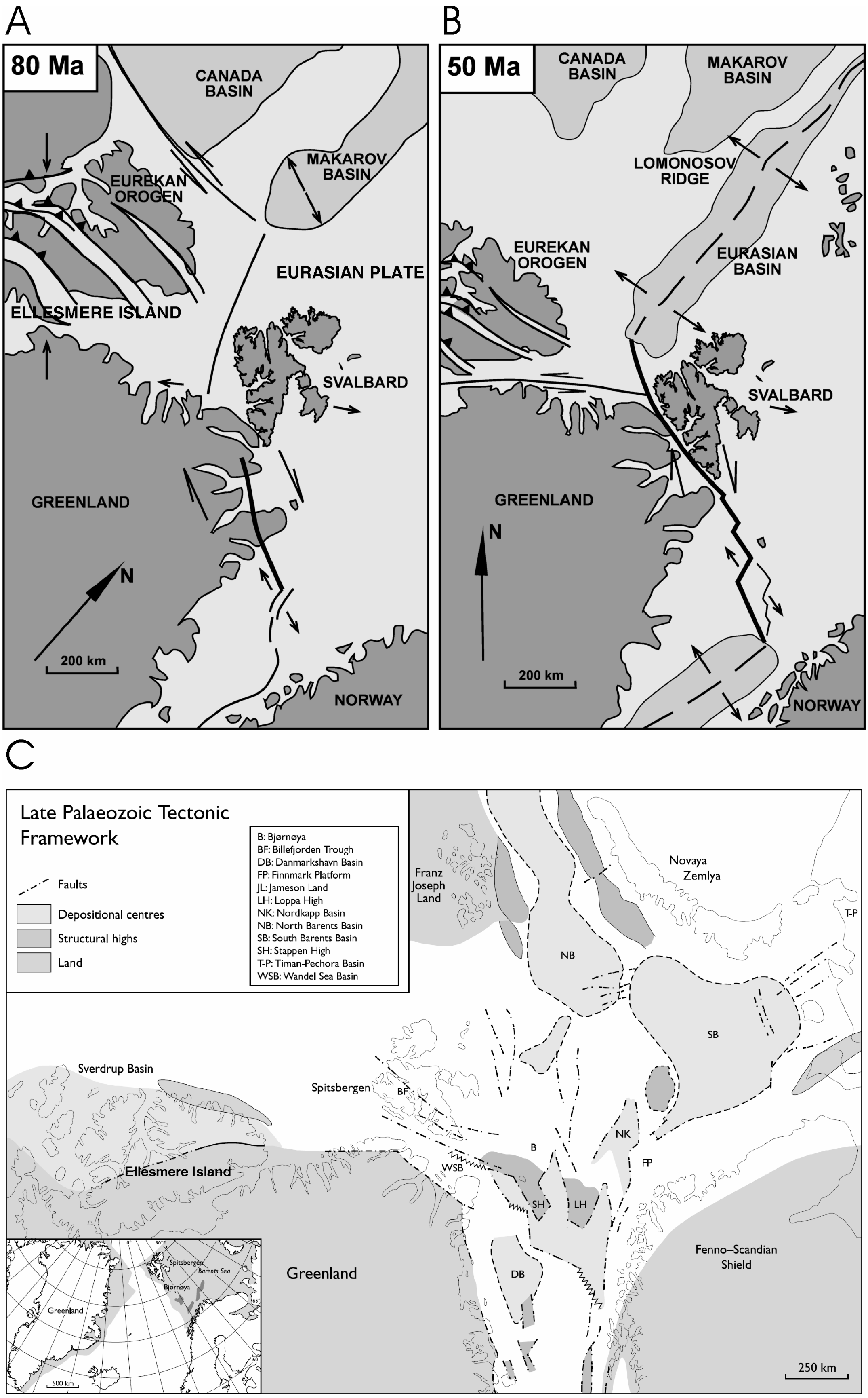

Fig. 2.3 Plate tectonic reconstruction model of Svalbard and Greenland from (A) Cretaceous and (B) Paleogene, after (Blythe and Kleinspehn, 1998). (C) Pre-drift reconstruction with structural element, after (Stemmerik and Worsley, 2005).

Together the Firkanten and Basilika Formations form an initial overall transgressive succession from the continental to marginal marine deposits of the Todalen Member, through shoreface in the Endalen Member to offshore transition in the Basilika Formation (Fig. 2.2). (Steel et al., 1981; Dallmann, 1999). The Kolthoffberget Member represents laterally equivalent offshore deposits to the Todalen and Endalen Members found in the southwest (Dallmann, 1999). The pebbly conglomerate of the Grønfjorden Bed is only found locally on the western margin of the basin (Ohta et al., 1992).

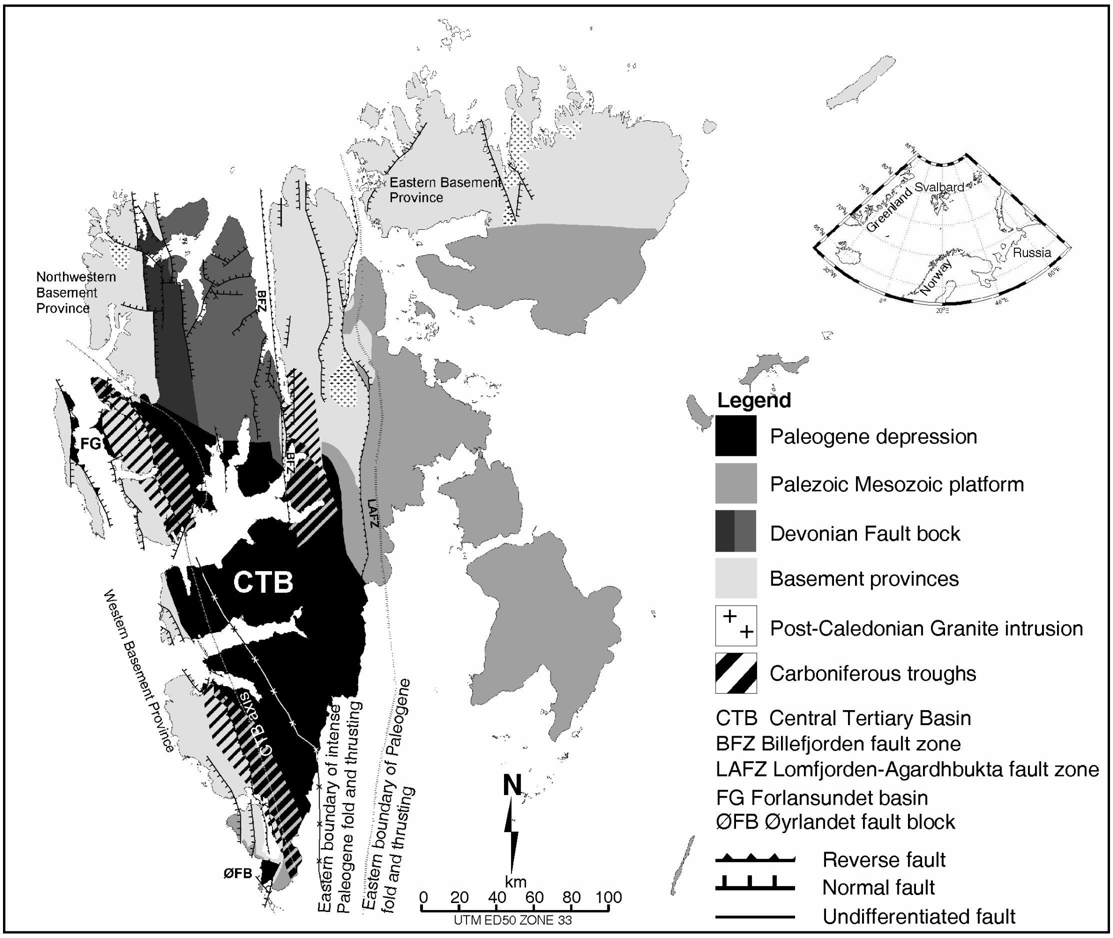

Fig. 2.4 Structural map of Svalbard, after (Dallmann, 1999).

The marine shale of the Basilika Formation is overlain by the progradational Grumantbyen Formation. The regional maximum flooding of the basin took place in the marine shale of the Frysjaodden Formation overlying the Grumantbyen Formation. The boundary between the Paleocene and Eocene is found approximately at this level (Steel et al., 1985; Manum and Throndsen, 1986; Dallmann, 1999; Nagy, 2005).

After the maximum transgression the Frysjaodden Formation marine shales were interrupted by small progradational sequences (the Hollendardalen Formation and the minor Bjørnsonfjellet Member) (Dallmann, 1999), which did not extend far into the basin. These smaller progradations preceded the large progradational section the makes the uppermost part of the sediments today. The regression covered the entire basin and extended from marine offshore (Frysjaoddden Formation) through shoreface (Battfjellet Formation) and marginal marine to continental (Aspelintoppen Formation) (Dallmann, 1999). According to the calculation of overburden (1.7 km) from vitrinite reflectance, the sedimentation continued for some time in the basin and probably extended further to the east (Manum and Throndsen, 1978). However, Spitsbergen was eroded extensively during the glacial periods in the Pliocene-Holocene (Blythe and Kleinspehn, 1998).

Previous depositional models

There is no single comprehensive depositional model for the Firkanten Formation regarding sediments, stratigraphy, and structural geology. In this section different former observations and interpretations are presented. These observations raised some questions to the earlier conclusions regarding the depositional environment, which will be addressed in later chapters.

The Todalen Member mainly consists of fine grained muddy sediments and coal. The Endalen Member is made up of thick well sorted sandstone sections and the Basilika Formation is characterised by bioturbated muddy siltstones (Dallmann, 1999).

The Firkanten Formation has been described as representing a fluvial delta system building out from east-northeast where the coal-bearing strata were deposited on the delta plain represented by the Todalen Member (Steel et al., 1981). The muddy organic facies were interpreted as floodplain and interdistributary bay deposits (Fig. 2.5). Tides and waves had supposedly influenced large parts of the delta (Steel et al., 1981; Steel and Worsley, 1984) and the tidal influence on the Todalen Member has been partially recognised as extensive.

The Endalen Member was interpreted as the sandstone deposits of a wave dominated shoreline delta front (Steel et al., 1981; Steel and Worsley, 1984; Bruhn and Steel, 2003), while the shale of the Kolthoffberget Member was the lower delta front to prodelta (Fig. 2.5) (Steel et al., 1981). The interpretation was based on the stratigraphic position to the Todalen Member delta plain. The Basilika Formation was interpreted as offshore transition deposits (Steel and Worsley, 1984; Steel et al., 1985; Dallmann, 1999).

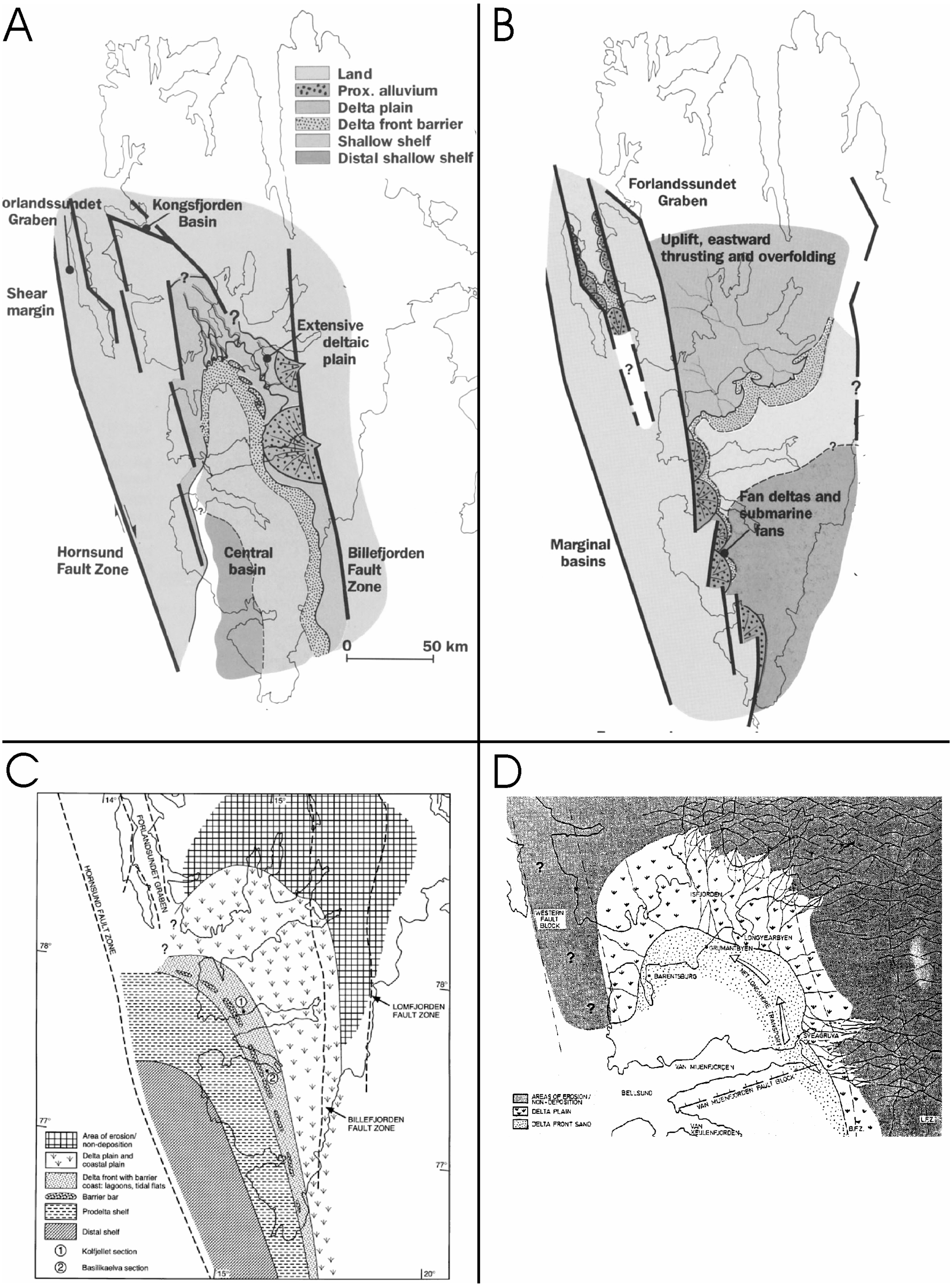

Fig. 2.5 Selected former paleogeographic reconstructions of the Firkanten Formation that raised some questions to the previous interpretations. (A) Paleocene and (B) Eocene, from (Worsley et al., 1986). (C) Firkanten Formation, from (Nagy, 2005). (D) Firkanten Formation, from (Nøttvedt, 1982).

The collection of interpreted depositional environments of the Todalen Member reveals a complex and confusing system of fluvial, wave, and tidal influence on a coastline that was described both as retrograding and progradational at the same time e.g. (Kalgraff, 1978; Steel and Dalland, 1978; Tønseth, 1981; Nøttvedt, 1982; Hansen, 2004). Apparently the interpretation of the Todalen Member as a fluvial delta was to a large extent based on the presence of coal, indicating continental environment. It also seems that the interpretation to some extent has been influenced by the presence of the fluvial conglomerate of the Grønfjorden Bed at the base of the Todalen Member.

The presence of clasts/pebbles in the deposits were interpreted to represent a mixed braided river/low-sinuosity fluvial setting (Nøttvedt, 1982). The conglomerates were interpreted as fluvial mainly on the lack of bioturbation (Hansen, 1982), the apparently random extent, and the poor sorting (Steel and Dalland, 1978). No distinction was made between pebbly conglomerate and angular mudclasts derived from the Carolinefjellet Formation or the Firkanten Formation.

The carbonaceous mudstone and coal of the Firkanten Formation have previously been interpreted as floodplain, levee, or interdistributary bay deposits on the basis of the fine grain size and the high organic content (Kalgraff, 1978; Steel and Dalland, 1978; Ytreland, 1980; Tønseth, 1981; Hansen, 1982; Wilhelmsson, 1999; Jochmann, 2004). The general floodplain interpretation of the mudstone seems to be based largely on the lack of marine observations like bioturbation and fossils (Steel and Dalland, 1978; Nøttvedt, 1982; Hansen, 2004), which are hard to identify in outcrop in the Todalen Member.

However, floodplain levee settings are normally expected to show larger input of clastic sediment than found in the Todalen Member and the extent of mires is supposed to be limited. Peat accumulations in active delta or floodplain environments tend to be thin and irregular (McCabe, 1984).

Steel and Dalland (1978) argued that a delta plain interpretation for the lowermost section of the Todalen Member was unlikely. This conclusion was based on the marine influence on the sediments and lack of evidence for a delta succession. The thickness of the Todalen Member below the first coal seam is too thin and largely influenced by the topography, which would not make it possibly for any delta to develop (Steel and Dalland, 1978). The lower part of the Todalen Member was found to be controlled by the underlying topography in the unconformity to the Carolinefjellet Formation (Steel and Dalland, 1978; Jochmann, 2004).

This section was therefore argued to be a gradual transgression of the area where the fluvial impact was expected to have been minor (Steel and Dalland, 1978).

From the lithostratigraphy it is known that the Firkanten Formation is an overall transgressive succession expected to be reflected in the deposits. The delta described in the Firkanten Formation is supposed to be a fluvial dominated delta system with a later wave influenced shoreline (Kalgraff, 1978; Steel et al., 1981). The deltaic coastal plain is described as developed during rising sea level (Nagy, 2005) indicated by coal deposits. However, elongated fluvial deltas, as described for the Todalen Member (Kalgraff, 1978) are normally related to progradation whereas typical retrograding coastlines display tidal flats or lagoons when there has been no prior valley incision (Boyd et al., 1992). These somewhat contradicting interpretations gave rise to the following two questions. These two questions and others raised later in this chapter will be discussed and answered in the following chapters. The answers are summarised in Chapter 8.2.

1. *Does the Todalen Member represent a fluvial delta system?*
2. *Why are the coal-layers thick and broad and why are there no extensive fluvial channel deposits in the sections?*

The interpretation of the fine grained sediments as subaqueous levees or interdistributary bays is related to the tidal influence found in the sediments reported throughout the Todalen Member (Kalgraff, 1978; Steel and Dalland, 1978; Steel et al., 1981; Tønseth, 1981; Hansen, 1982; Wilhelmsson, 1999; Jochmann, 2004). These sediments are described as related to tidal mud flat deposits (Kalgraff, 1978; Steel and Dalland, 1978; Nøttvedt, 1982), deltaic coastal plains with lakes and swamps, or possibly related lagoons that developed during rising sea level (Kalgraff, 1978; Steel and Dalland, 1978; Wilhelmsson, 1999; Jochmann, 2004; Nagy, 2005) based on marine influence, high organic content, barren of foraminifers, and absence of calcareous taxa (Nagy, 2005). The limited evidence of macrotidal impact indicates a moderate tidal environment (Ytreland, 1980).

The tidal deposits have also been interpreted as estuaries from flooding of the fluvial valley system (Steel and Dalland, 1978; Hansen, 1982; Nøttvedt, 1982). However, there is no convincing evidence of valley incision from sea level fall described from the Todalen Member and therefore:

3. *Were there estuaries in the Todalen Member?*

Hansen (1982) argues for a back barrier bar system since the fine grained sediments deposited in tidal flat and lagoon areas in the Todalen Member indicate protection from storm and wave influence. The extent of the tidal deposits is large (Steel and Dalland, 1978) indicating a broad flat coastal plain.

The sandstone sections in the Firkanten Formation have previously been separated into two different settings; crevasse splays or fluvial channels on a delta plain in the Todalen Member and barrier bars/mouth bars of a delta front in the upper Todalen Member and in the Endalen Member (Kellogg, 1975; Steel et al., 1981; Jochmann, 2004). The crevasse splay or fluvial levee interpretations were based on the lack of shells, high content of organic debris, and occasionally rooted tops (Kalgraff, 1978; Steel and Dalland, 1978; Hansen, 1982; Nøttvedt, 1982).

Conglomerates occur in these beds as pebble filled scours and thin pebbly laminae, interpreted as crevasse splays (Steel and Dalland, 1978), fluvial chute bars (Tønseth, 1981; Nøttvedt, 1982), or related to beach deposits (Kalgraff, 1978). The sheet-like pebbly laminae were interpreted as post-storm deposited gravel lags (Nøttvedt, 1982).

Conglomeratic cross stratified bedforms are described from the Endalen Member (Bruhn, 1999). These were interpreted as braided river system but occur in an otherwise foreshore/shoreface setting overlain by low angle cross laminated to plane laminated beach sandstone. The conglomerates at the boundary between the Firkanten and Basilika Formations were interpreted as fluvial deposits analogous to the Grønfjorden Bed and related to sea level fall (Kalgraff, 1978; Bruhn, 1999) but the arguments are not conclusive and therefore this question was raised.

4. *How were the conglomeratic beds deposited and where were the pebbles generated?*

Bioturbated sandstone with hummocky and swaley cross stratification, wave ripple lamination, *Ophiomorpha,* and *Planolites* has been described from the Firkanten Formation and interpreted as shoreface or upper delta front (Kalgraff, 1978; Ytreland, 1980; Nøttvedt, 1982; Bruhn, 1999; Wilhelmsson, 1999; Jochmann, 2004). In the western part of the basin the wave dominated shoreface succession is green in colour (Nagy, 2005), possibly indicating high glauconite content.

The intensively bioturbated sandstone was interpreted as lower delta front or prodelta/offshore transition wave influenced setting (Kalgraff, 1978; Ytreland, 1980; Hansen, 2004; Jochmann, 2004). The interpretation of the distal sections of the Firkanten Formation as prodelta was based on the relation to the interpreted delta plain of the Todalen Member. However, as a consequence of question 1:

5. *If the Todalen Member does not represent a delta plain setting, then what do the Endalen Member and the Basilika Formation represent?*

Basin model of transtension-transpression

In the late Cretaceous, Svalbard was located adjacent to North Greenland and Ellesmere Island (Fig. 2.3) (Blythe and Kleinspehn, 1998). The West Spitsbergen Fold and Thrust Belt (Fig. 1.1 and 2.4) was created due to plate shortening in connection to the opening of the North Atlantic (Lyberis and Manby, 1993; Harland, 1997).

The previous model (transtention-transpression) of the formation of the Central Tertiary Basin was based on the stratigraphic record of transgressive-regressive cycles (Steel et al., 1981) and missing evidence for extensive uplift in the west in the Early Paleocene (Steel et al., 1985). According to this model the basin was initially formed during a period of transtention (Steel et al., 1985) represented by the initial transgressive succession in the Paleocene, the section from the unconformity at the base of the Firkanten Formation to the top of the Grumantbyen Formation (Fig. 2.2). This early phase of the basin was believed to be characterised by delta progradation from east towards south-southwest (Fig. 2.6) (Steel et al., 1985). However, there are no indications of substantial uplift and erosion east of the basin of the Mesozoic strata and therefore:

6. *Where did the sediments in the Firkanten Formation come from?*

According to Steel et al. (1985) the basin configuration changed to transpressional in the Eocene and was characterised by two regressive phases in the succession from the base of the Frysjaodden Formation to the top of the Aspelintoppen Formation. The progradation was at this point from west to southeast. The drainage reversal was interpreted as evidence for a late onset of the thrust belt after the formation of the basin (Steel et al., 1985). In the late Eocene and early Oligocene the plate movement was oblique slip before the rifting and sea floor spreading started in the Oligocene (Steel et al., 1981; Steel et al., 1985). This model raised the question:

7. *How was the basin formation related to the thrust belt?*

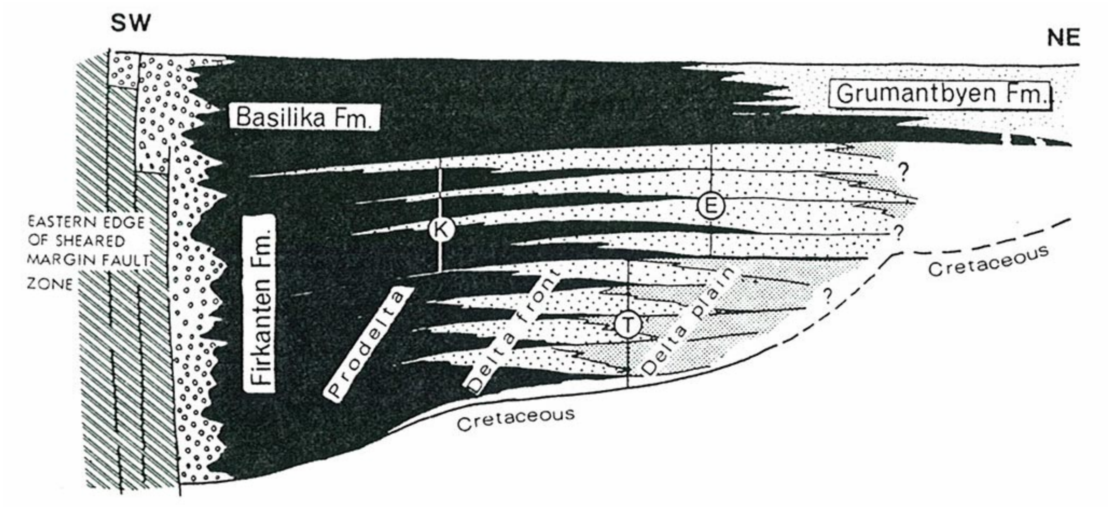

Fig. 2.6 Extensional model during the early basin development. T is the Todalen Member, E the Endalen Member, and K the Kolthoffberget Member, from (Steel et al., 1981). The early transgressive phase represents the transtensive phase and the overlying progradation is the transpressive part.

Basin model of a foreland basin

The newer model (foreland basin flexural loading) suggests that the Central Tertiary Basin was formed as a flexural depression in front of the fold and thrust belt (Bruhn and Steel, 2003). Recognition of compressional structures throughout the Paleocene and Eocene succession indicates overall compression during basin formation, with no initial extension, but with a strike-slip component (Braathen et al., 1995; Bergh et al., 1997; Braathen et al., 1999). A foreland basin, with an adjacent peripheral bulge, was suggested to have been created by flexural loading of the crust in connection to plate shortening in the thrust belt (Bruhn and Steel, 2003). The deformation might have been influenced and bounded by the Billefjorden and Lomfjorden-Agardhbukta fault zones to the east (Fig. 2.4) (Bergh et al., 1997). The sediment source during the early transgressive succession was from the peripheral bulge (Fig. 2.7) and not until later did the thrust belt start to shed sediments (Bruhn and Steel, 2003). However, in general the uplift of a foreland bulge is relatively minor compared to the thrust belt in a foreland basin setting and therefore:

8. *Could the peripheral bulge have been a source of sediments for the Firkanten Formation?*

Before the sea floor spreading started in the Oligocene there was a period of extension (Braathen and Bergh, 1995; Blythe and Kleinspehn, 1998; Braathen et al., 1999). The Miocene was characterised by denudation while the glaciations in late the Cenozoic efficiently eroded the area (Blythe and Kleinspehn, 1998).

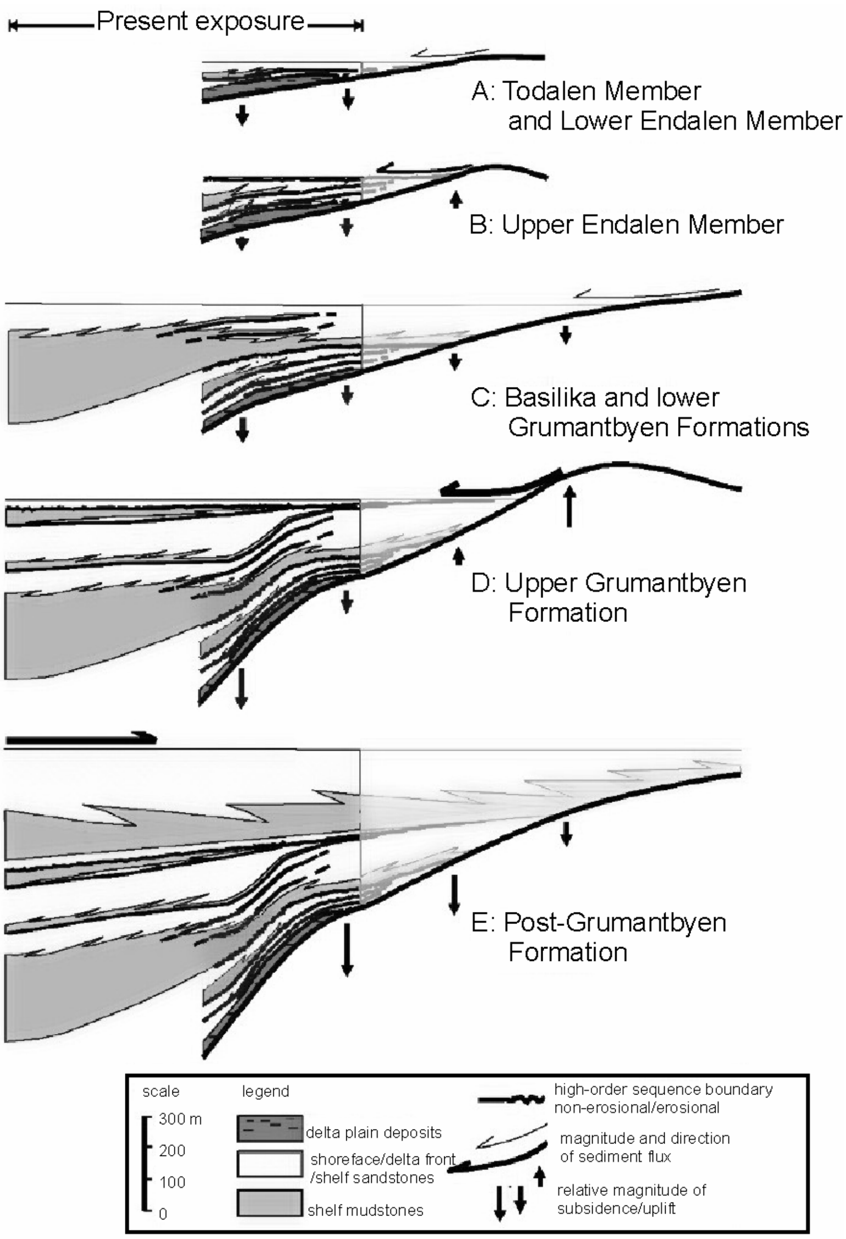

Fig. 2.7 Development of depositional the architecture in the Firkanten, Basilika and Grumantbyen Formations, after (Bruhn and Steel, 2003).

Paleogene climate

The climate at Spitsbergen in the Paleocene and Early Eocene based on fossil plant material has been interpreted to be warm-temperate with a high humidity equally distributed over the year (Golovneva, 2000) even if the latitude has been reconstructed to 65-68^{o} N (Cepek and Kruttzsch, 2001). The temperature rarely dropped below 0 ^{o}C (Schweitzer, 1980). In the Late Eocene the climate changed to almost cool-temperate (Golovneva, 2000). From the Paleocene to Eocene there is recorded a general climatic change in the northern hemisphere towards a colder climate (Wolfe, 1980). The climate seems to have been favourable in the Paleocene on Spitsbergen for mammal plant eaters like Pantodonts, of which there are found traces (Lüthje et al., Submitted).

Dating of Paleogene strata

The Tertiary coal-bearing strata on Svalbard are described as of Paleocene age (Michelsen and Khorasani, 1991; Cmiel and Fabianska, 2004). Dating the Paleogene strata on Svalbard is complicated due to the poor fossil record from the sediments and the extensive cementation, which makes it difficult to gain any material for dating. However, from sparse material of palynology, spores, plant fragments, and molluscs a Paleocene age can be concluded for the Firkanten Formation (Livsic, 1974; Schweitzer, 1980; Manum and Throndsen, 1986; Nagy et al., 2000; Nagy, 2005). Late Paleocene calcareous nannofossils are described from the Firkanten Formation in the southern part of the basin (Cepek, 2001). The boundary with the Eocene is above the Grumantbyen Formation in the shale of the Frysjaodden Formation (Fig. 2.2) (Livsic, 1974; Steel et al., 1981).

2.2 General coastal depositional environments

A depositional coastline consists of an inner continental section, a marginal marine, a shallow marine, and a marine section. The marine sections are divided according to the amount of wave, storm and tidal energy working on the sediments (Fig. 2.8) (Reading and Collinson, 1996). The most marine zone (below the mean storm wave base) is the offshore. This is separated from the shoreface (above mean fair-weather wave base) by the offshore transition or the lower shoreface. The foreshore is above the mean low water mark, representing a zone of high energy with breaking waves washing up on the beach. The beach represents the

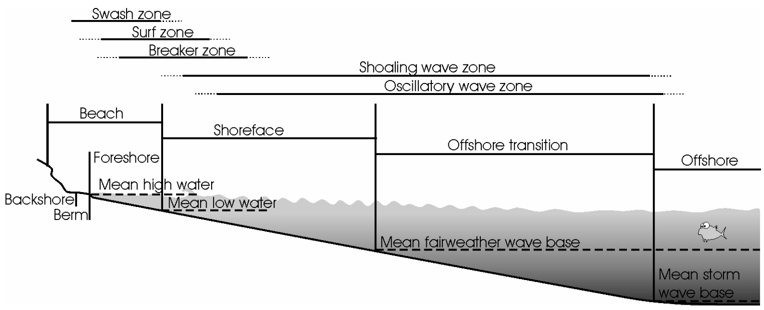

Fig. 2.8 Classification of a coastline into different environmental zones, according to water depth and the energy regime acting on the coast; wave, storm, and tidal, after (Reading and Collinson, 1996).

subaerial part of the coast. The foreshore consists of the break, the surf and the swash zone, of which the breaker zone extends out to the upper shoreface (Reading and Collinson, 1996). On the coastal side of the foreshore are the un-vegetated backshore and the continental area. The different zones of the near shore are characterised by:

- *Offshore*

Below the mean storm wave base, sedimentation is dominated by hemipelagic settling but coarse sediment can be transported out by large storms or turbidity currents. The bioturbation in this zone can be intense.

- *Offshore transition*

The sediments in the section above the mean storm wave base but below mean fair-weather wave base is dominated by storm deposits with hummocky and swaley cross bedded sand interrupting the otherwise fine grained bioturbated hemipelagic mud. The section is characterised by shifting high and low energy intervals.

- *Shoreface*

Closer to the shore, at the shoreface, the sand layers become thicker and more amalgamated. Normally oscillatory and shoaling waves act on the shoreface breaking in the upper part. This is also a zone of intense bioturbation during periods of fair-weather. Strong, wave or tidally induced currents can have a large effect on sediment transportation and shaping of the shoreface. During storms the shoreface can be largely eroded, and coarse material can be washed up on the beach or transported further out off shore.

- *Foreshore*

The foreshore, which includes the beach, often display well-sorted sandy sediments washed by waves. However, all coastal deposition depends on the source of sediment and type of material available for deposition, which will also influence the shape of the coast.

- *Backshore*

The backshore can be mud prone since it is an area of much lower energy level than the foreshore. It is protected from wave energy by the barrier bars and islands built up on the foreshore. In the coastal backshore areas there can be extensive mud tidal flats, swamps, marshes, and further inland on the coastal plain peat bogs (Reading and Collinson, 1996).

Depositional coastlines have been classified according to the dominant energy regime configuring the coast and the general development of the depositional basinal setting (Fig. 2.9). The three energy regimes are fluvial, wave or tidal influence (Boyd et al., 1992). A coast will often be influenced by all three energy regimes but with one dominant part. In addition coastal areas dominated by the same energy regime will show different development if the base level is rising or falling, that is, if the system is retrograding or prograding. A wave dominated coastline in a retrograding or rising base level setting will develop barrier bars and islands and adjacent lagoons. However, during base level fall a wave dominated coast will be characterised by strandplains and cheniers. Fluvial dominated coastlines are in general prograding since the high sediment supply forces the coastline to prograde even during rising sea level. During increased base level the river mouth would drown and develop into an estuary. This general division of the coast gave rise to the following question.

9. *What type of depositional coastline is represented in the Firkanten Formation?*

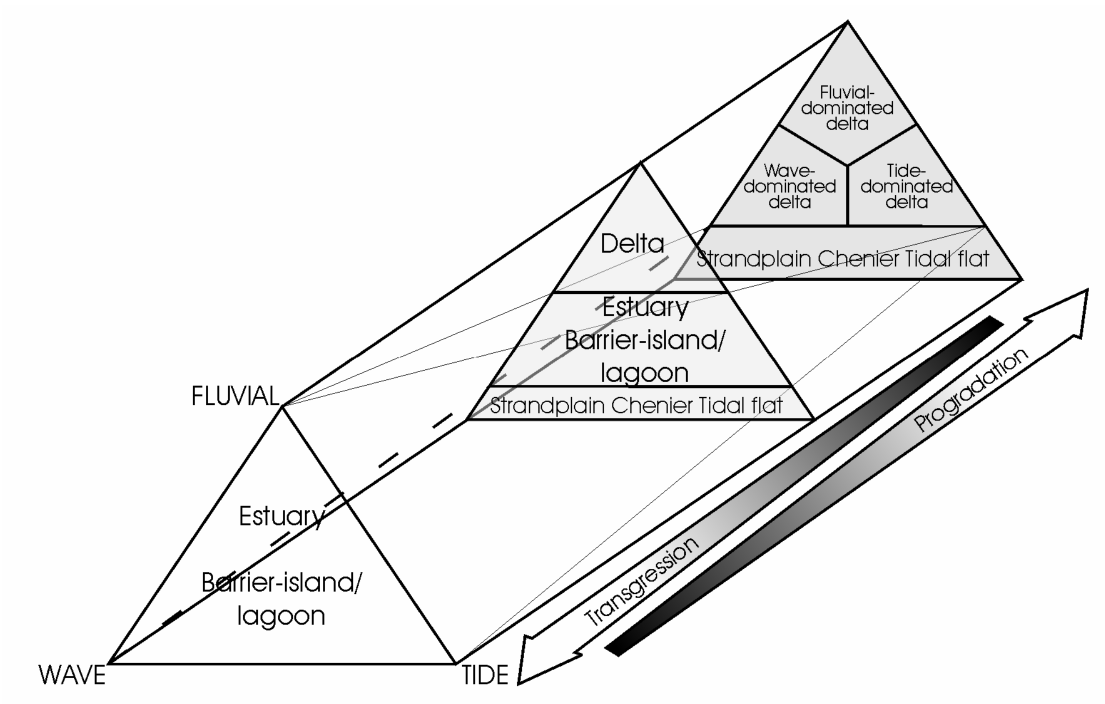

Fig. 2.9 Coastal classification scheme of the relation of coastal depositional environment to relative sea level changes separated according to dominant energy/sediment input, fluvial wave or tidal and to the general basin development, prograding or retrograding, after (Boyd et al., 1992).

2.3 Peat accumulation and the prerequisite for coal deposits

Peat, the precursor to coal, accumulates typically in environments where there is substantial vegetation growth, sufficient standing water to reduce degradation, an absence of inorganic sediments, and creation of accommodation space (Fig. 2.10) (Ward, 1984; Bohacs and Suter, 1997). The paleoflora is among other things influenced by the geological age, physiographic setting, climate, and nutrient availability. Climate, which includes temperature, humidity, and seasonal fluctuations influences the decomposition and is itself controlled by the paleogeography (Ward, 1984). Degradation depends on, among other things, water table level and fluctuations of this.

The paleoecological parameters of the mire, like water depth, chemistry and nutrient supply control the type of peat accumulated, which in turn will influence the coal characteristics (Nichols, 1995). Nichols (1995) summarizes the work by (Teichmüller, 1958) into four different mire type reconstructions for Cenozoic coals; the reed mire, the Nyssa-Taxodium forested swamp, the brush mire, and Sequoia forest based on modern analogues and represented by different hydrologic environments. The peat production rate is controlled by climate, type of flora, and supply of water and nutrients. Preservation of organic plant material takes place when oxidation and decay by bacterial and/or fungal activity are limited, for example, below the groundwater table.

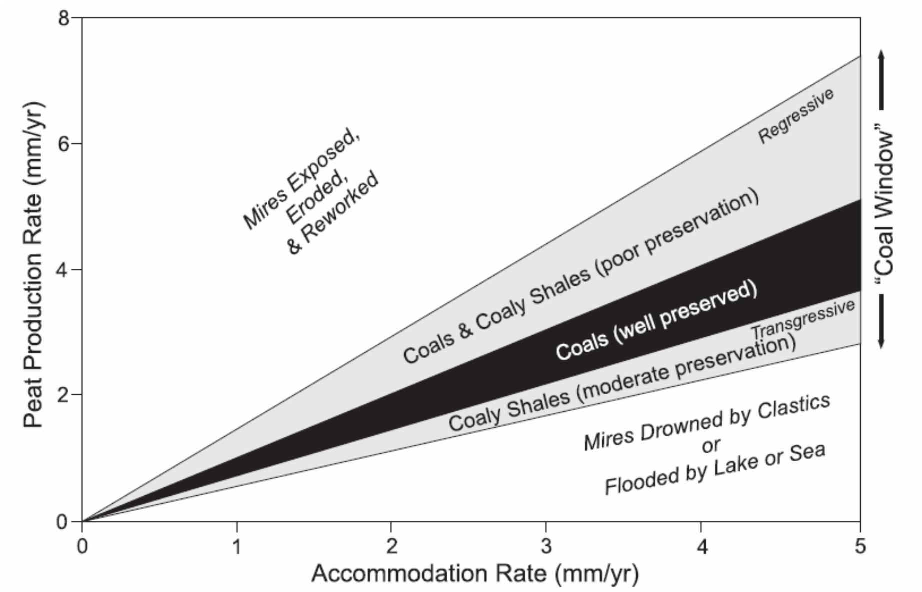

Fig. 2.10 The coal window, representing where peat can be accumulated and preserved, is where the rate of organic production is in balance with the rate of accommodation space created, from (Davies et al., 2005) after (Bohacs and Suter, 1997). If too much accommodation is created the mire will be drowned and if too little it will be denuded. The grey areas are conditions where organic-rich sediments are deposited with various contents of siliciclastics and organic material.

The creation of accommodation space is controlled by eustacy, tectonic, and general subsidence from compaction. As stated, coal accumulations are found in basins with little or no clastic input and where the base level (mostly groundwater table) and organic production are in pace (Teichmüller, 1989), or where the peat production rate and the creation of accommodation space are in balance (Bohacs and Suter, 1997). Even if the sediment input of inorganic clastic material is too high there can still be organic material deposited. However, these sediments will not form proper coal seams (Fig. 2.10).

The organic material is altered during the peatification process to form peat. Coal is produced by diagenesis of organic material such as peat during burial, called coalification. During the coalification process peat is converted into coal with increasing rank from peat, lignite (brown coal), sub-bituminous, bituminous, and anthracite. The rank of the coal is determined by the level of geochemical alteration that has taken place. This is controlled by pressure and temperature, where temperature is the most important factor. An increased temperature leads to increased rank and thereby increased carbon content, virtinite reflectance, and calorific value (kcal/kg) e.g. (Teichmüller, 1987; Teichmüller, 1989). There is in addition an increase in loss of water and volatile matter.

Peat accumulating environments can be rheotrophic or ombrotrophic, which will influence the grade of the peat and the coal. Rheotrophic environments (swamps) can be fresh or brackish (limnic or paralic respectively) but commonly the water supply comes from groundwater, precipitation, and surface runoff. In ombrotrophic environments (bogs) the main water supply is from precipitation and the bog surface is often domed (Scott, 1987).

Different types of peat are formed by vascular plant (humic) and algal (sapropelic) material (McCabe, 1984; Scott, 1987). Banded humic coal consists of a heterogeneous mixture of plant debris, while non-banded sapropelic coal is made up of homogeneous spores and algal material (Ward, 1984).

Coal macerals

The main coal maceral groups are vitrinite, liptinite, and inertinite. The maceral composition reflects the coal/peat composition and is therefore related to the depositional environment, tectonic setting, paleoflora, paleoclimate, and paleogeography (Ward, 1984; Teichmüller, 1989; Shearer et al., 1995; Bohacs and Suter, 1997; Scott, 2002; Moore and Shearer, 2003) but depends also on several other parameters, such as degradation, alteration, and digenesis (Wüst et al., 2001). There is no direct connection to any single factor but is an interacting relationship.

Vitrinite is the most common maceral in most coal. Vitrinite is derived from cell wall material (woody tissue) of plants, which are chemically composed of the polymers, cellulose and lignin, detrital material, and gels e.g. (Ward, 1984; Teichmüller, 1989; Scott, 2002). The cellulose is degraded during peatification/coalification, while the lignin is more resistant. The cell structures are often preserved (Scott, 2002). Liptinite, which is a diverse group (Scott, 2002) is derived from waxy and resinous parts of hydrogen-rich plants and decomposition products (Teichmüller, 1989). The inertinite macerals, which is a controversial group, are derived from plant material that has been strongly altered. Several different origins of inertinite have been discussed and have often been referred to in the literature as an indication of desiccation, oxidation, and fungal degradation, which in turn would indicate a raised bog (Sweet and Cameron, 1991) or falling base level (groundwater).

Origin of fusain

Inertinite is often represented by fusain. Scott (1989) discusses the origin of fusain (fusinite and semifusinite) as representing fossil charcoal. Jones and Chaloner (1991) argue, based on comparison of experimentally produced charcoal and fossil material that the origin of typical fusain is fossil charcoal. Only fire has been proven to create fusain by the charring process (Scott, 1989). To form charcoal burning with limited access to oxygen (Scott, 1989) as created in a charcoal stack, is needed. Therefore, it can be concluded that charring is rather the opposite of the oxidation by desiccation.

Fusain is mainly made of wood and fibres. Lignin rich plants like gymnosperms are more easily charred since lignin is more prone to produce charcoal than other plant materials such as herbaceous plants, and could therefore be overrepresented in fusain (Scott, 1989). However, this does not exclude that other macerals of the inertinite group could have an origin other than fire.

A possible connection between low water table and high inertinite content could be that an area of low water table is more prone to burn. However, Scott (1989) shows that modern wildfires can occur in waterlogged areas and do not have to be preceded by long periods of drought.

Maceral of coal from Svalbard

There is a noticeable difference in the inertinite maceral content between the lower and upper main coal seams of the Paleocene coal on Svalbard (Michelsen and Khorasani, 1991; Cmiel and Fabianska, 2004; Orheim et al., 2007). Globally, Paleocene coal is often high in inertinite while Eocene coal has low inertinite content (Shearer et al., 1995).

The Paleocene record of the Firkanten Formation on Svalbard contains traditionally five coal seams; Svea, Todalen, Longyear, Svarteper, and Askeladden. The Svea seam is high in inertinite (> 10 %, mostly 30-50 %) like other Paleocene coals while the upper main coal seams (Longyear seam) show particularly low inertinite content similar to Eocene coal (< 10 %) (Michelsen and Khorasani, 1991; Cmiel and Fabianska, 2004; Orheim et al., 2007). The other three minor seams are also low in inertinite content similar to the Longyear seam (Orheim et al., 2007).

2.4 General flexural formed basins

Flexural basins are formed from flexural response of the crust to stress. Foreland basins are a common type of flexural basins and are formed under compression (Allen et al., 1986; DeCelles and Giles, 1996). They can be divided further into 1. The Alpine type peripheral foreland basins related to continent-continent collision and 2. The Laramide type retro-arc foreland basins related to lithospheric subduction (Dickinson, 1974; Catuneanu, 2004). The basin represents a potential depositional centre for sedimentary accommodation that can be separated into, counting from the thrust belt; wedge-top, foredeep, forebulge, and back-bulge areas (Fig. 2.11) (DeCelles and Giles, 1996).

The formation of the foreland basin is largely controlled by the properties of the lithosphere. When the crust is topographically loaded in the fold and thrust belt, the increased weight will make the crust flexure and bend down forming a basin in front of the thrust front (DeCelles and Giles, 1996). The load and therefore the subsidence will be greatest closest to the fold and thrust front (Fig. 2.12) (Catuneanu and Sweet, 1999). Narrow steep foreland basins have been suggested to form from plastic compressional folding of the crust rather than simple loading (Fig. 2.13) (Zhang and Bott, 2000). Depending on the rigidity of the crust it will bend in a sinusoidal waveform of anticlines and synclines of progressively decreasing wavelength, which decay away from the fault zone. The foreland bulge is the first anticline but is mostly not a prominent high. The sediment accumulation in the basin will lead to further subsidence (DeCelles and Giles, 1996). During periods of tectonic quiescence the mountain belt is eroded, which will lead to uplift of the basin (Fig. 2.12) (Catuneanu and Sweet, 1999). The different stages of the development are recorded in the sedimentary strata (Heller et al., 1988) and therefore the sedimentary pattern can be used for understanding the basin formation. Foreland basins are elongated and have an asymmetrical pattern, which is displayed in the sedimentary record across the basin.

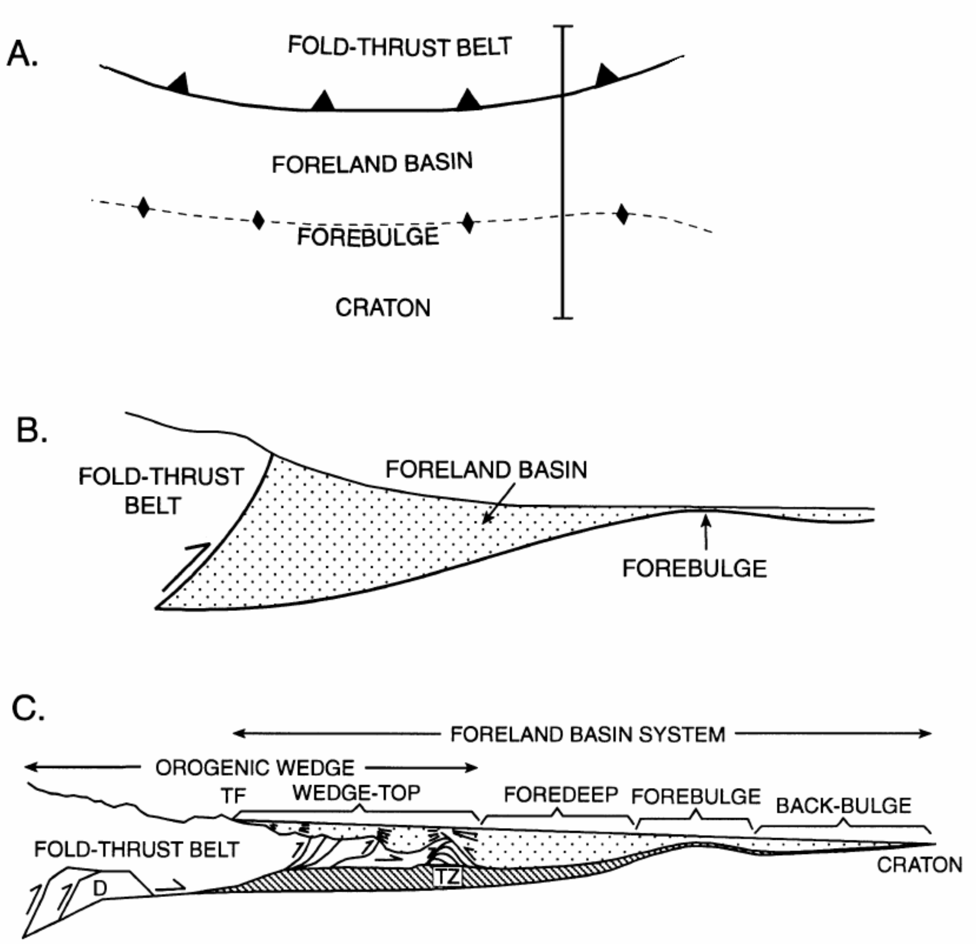

Fig. 2.11 Schematic view and cross section of a foreland basin, after (DeCelles and Giles, 1996). (A) Structural map of a foreland basin. The vertical line indicates the orientation of the cross section shown in B. (B) Simplified cross section of a foreland basin, with the fold and thrust belt, foreland basin and bulge. Not to scale. (C) Revised concept of a foreland basin system, with wedge-top, foredeep, forebulge, and back-bulge depositional centres.

The peripheral foreland basin can be characterised by two types of development: 1. The Pyrenean type formed on full continental crust with an initial continental or shallow marine sedimentation often with axial inflow of sediments (Hirst and Nichols, 1986) and 2. The true Alpine type with initial deep marine sedimentation (Covey, 1986) formed on an initial thinned crust. The Alpine foreland basins are sometimes referred to as going from an underfilled flysch stage with deep marine sedimentation to a filled or overfilled molasse stage of terrigenous sedimentation (Allen et al., 1986; Sinclair, 1997).

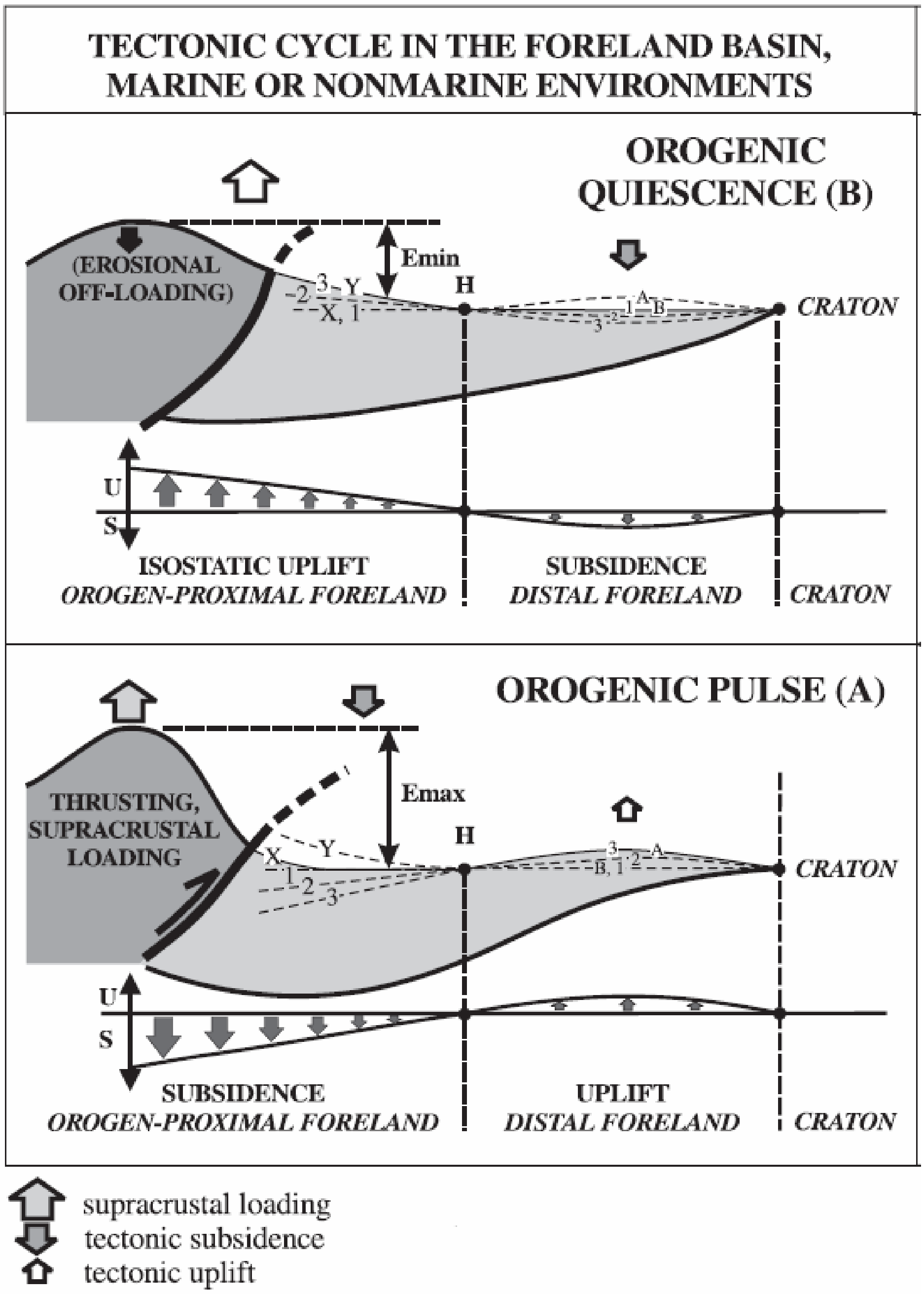

Fig. 2.12 Flexural model of a foreland basin showing the uplift and subsidence during (A) orogenic pulse and (B) tectonic quiescence, after (Catuneanu and Sweet, 1999). The vertical scale of the distal foreland or bulge is exaggerated for clarity. Emin and Emax are minimum and maximum difference in elevation between sediment source area and the proximal surface profile. X is the topography at the end of the pulse stage while Y is the surface profile at the end of the quiescence stage. 1 is the horizontal plane at the beginning of the respective periods and 2 and 3 show the evolution in time. U is uplift and S subsidence where H is the hinge line between the two.

The Central Tertiary Basin formation was formed as a foreland basin related to the West Spitsbergen Fold and Thrust Belt (Bruhn and Steel, 2003). The fold and thrust belt was formed due to convergence between Svalbard and Northern Greenland (Manby and Lyberis,

2000) on a full continental crust. This indicates that the Central Tertiary Basin could be classified as an Alpine type foreland basin of continent-continent collision. The Firkanten Formation represents the first deposits in this basin and is characterised by clastic continental and shallow marine deposits. The Central Tertiary Basin is therefore expected to have formed as a Pyrenean type of peripheral foreland basin and to investigate this further the following question was raised.

10. How did the Central Tertiary Basin form?

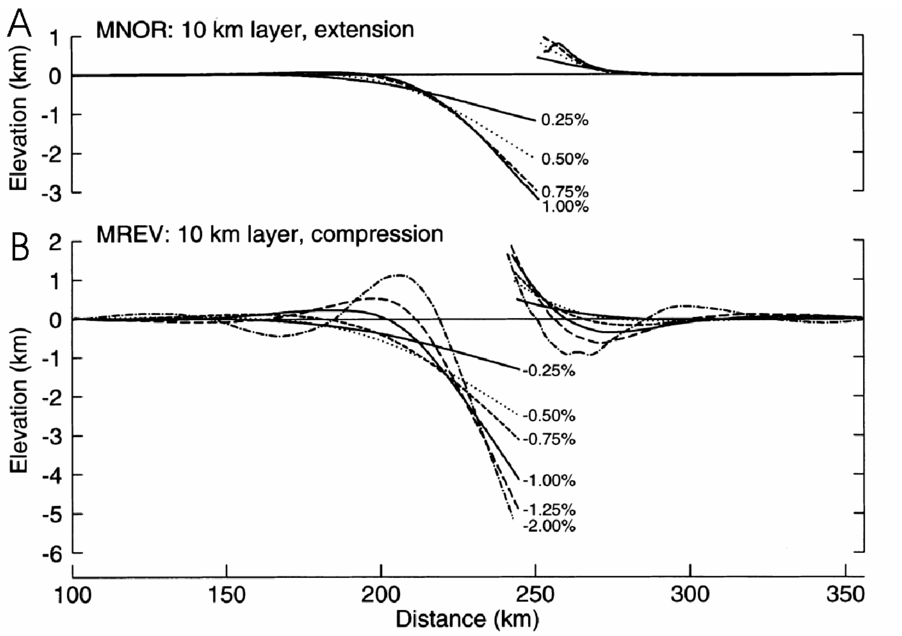

Fig. 2.13 Modelled basin profiles of (A) extensional normal faulted model versus (B) compressional 10-km-thick reverse faulted model development. The stacked flexure profiles compare the evolution to increased stretching (0.25% to 1.00% strain) respectively shortening (−0.25% to −2.00% strain), after (Zhang and Bott, 2000).

2.5 Questions raised

The questions raised to the previous interpretation address the type of depositional environment the Firkanten Formation represents and how it developed through time. They also indicate that there are inconsistencies in the interpretation of the formation of the Central Tertiary Basin. There are uncertainties in understanding the sediment drainage and where to find the provenance area of the sediments. These are the specific questions:

1. Does the Todalen Member represent a fluvial delta system?
2. Why are the coal-layers thick and broad and why are there no extensive fluvial channel deposits in the sections?

3. Were there estuaries in the Todalen Member?
4. How were the conglomeratic beds deposited and where were the pebbles generated?
5. If the Todalen Member does not represent a delta plain setting, then what do the Endalen Member and the Basilika Formation represent?
6. Where did the sediments in the Firkanten Formation come from?
7. How was the basin formation related to the thrust belt?
8. Could the peripheral bulge have been a source of sediments for the Firkanten Formation?
9. What type of depositional coastline is represented in the Firkanten Formation?
10. How did the Central Tertiary Basin form?

Subjects related to the depositional environment, questions 1-5 and 9 are discussed in Chapter 4. Questions 3, 5, and 9 relate to the development of the basin and are addressed in the sequence stratigraphic discussion in Chapter 5. Chapter 6 concerns the structural formation of the basin and addresses questions 4, 6-8, and 10.

3. SYNOPSIS OF ARTICLES

In this chapter a synthesis of the results of the research that form the basis of the articles presented in Chapters 4-7 is presented. The questions raised to the previous interpretation are discussed but are addressed in more details in the individual articles.

This research of the Firkanten Formation resulted in three articles regarding the depositional environment, the paleogeographic development, and the basin formation and configuration. These articles are presented in Chapter 4-6 respectively. In addition tracks of the mammal Pantodont were discovered in the mine, Gruve 7. The result from this work is presented in Chapter 7. Below, a synopsis of the main discussion and results of the articles is found.

The Firkanten Formation is the lowermost deposit in the Central Tertiary Basin on Spitsbergen, representing the main deposit of Paleogene strata on the island (Figs 1.1 and 2.2). It rests on the low angle unconformity to the Lower Cretaceous Carolinefjellet Formation (Steel et al., 1981; Dallmann, 1999).

The systematic investigation of the facies of the Todalen and Endalen Members, based on new cores and field data resulted in a new model for the depositional environment. A facies model was developed in combination with a sequence stratigraphic interpretation and a paleogeographic reconstruction in a three dimensional view, through time. According to this depositional model, the Todalen Member represents the coastal zone and the Endalen Member the adjacent shoreface and foreshore (Lüthje and Nichols, Submitted a).

The new depositional model and paleogeographic reconstruction recognises that the fluvial impact on the sedimentation was more limited than previously anticipated for the Todalen Member, previously described as representing a fluvial delta system e.g. (Steel et al., 1981; Steel et al., 1985; Dallmann, 1999). The Todalen Member is more correctly described as a wave dominated depositional coastal plain with microtidal influence.

Stratigraphically, the Endalen Member is situated above the Todalen Member, which indicates a retrograding succession confirmed by the sequence stratigraphic model (Lüthje and Nichols, Submitted b). The system showed an overall back-stepping retrograding coastline, where transgression took place during major flooding events. In between the major floodings the succession was aggrading. The coastal transgression followed the outline of the basin limited to the north, west, and east, but opening up towards the south.

Provenance study of the sediment indicates that the source was the fold and thrust belt in the west and the uplifted and eroded northern area (Figs 1.1 and 2.4). Sandy sediments entering the basin close to the thrust front from the uplifted northern section were re-deposited in the basin as sandy beaches on the foreshore. Inland of the foreshore there were large tidally influenced lagoons and tidal flats gradually transferring into coastal plain swamps and peat mires. Some minor fluvial channels were probably present but insignificant for the sedimentary record. Coarse grained pebbly sediments were shed into the basin from the thrust front, indicated by the provenance of pebbles and the alluvial fan/delta of Grønfjorden Bed. These pebbles were sorted while being transported in the basin. The pebbles were deposited on the foreshore and washed-over into the lagoons during storms. The coast was dominated by wave and storm influence.

The sedimentary depositional model for this lowermost part of the Central Tertiary Basin and the provenance of the sediments from the fold and thrust belt and uplifted northern area provided further implications for the interpretation of the tectonic basin development (Nichols and Lüthje, Submitted). The previously suggested models for the Central Tertiary Basin development; the transtension/transpression (Steel et al., 1981) and the foreland basin flexural loading model (Bruhn and Steel, 2003) were considered. The thrust belt was uplifted and eroded prior to sedimentation in the basin, indicating a compressional flexural basin (Nichols and Lüthje, Submitted). However, the new model suggests formation mainly through compressional folding rather than flexural loading, which is in accordance with initial continental/shallow marine sedimentation and the formation of an asymmetrical deep narrow basin as well as the narrow thrust belt and the almost vertical folding of strata on the western side.

3.1 Depositional environment

The depositional environment in the Firkanten Formation was a wave energy dominated coast. The conceptual model of the depositional environment from the facies analysis is presented in Fig. 3.1. The fine grained muddy and carbonaceous deposits of the Todalen Member represent the costal plain and the well sorted sandstones of the Endalen Member represent the foreshore and shoreface. The lower shoreface and offshore transition is represented by muddy bioturbated sandstone of the Endalen Member and the Basilika Formation. The facies analysis resulted in definitions of numerous subfacies that were combined into ten facies. These were further interpreted as representing four different

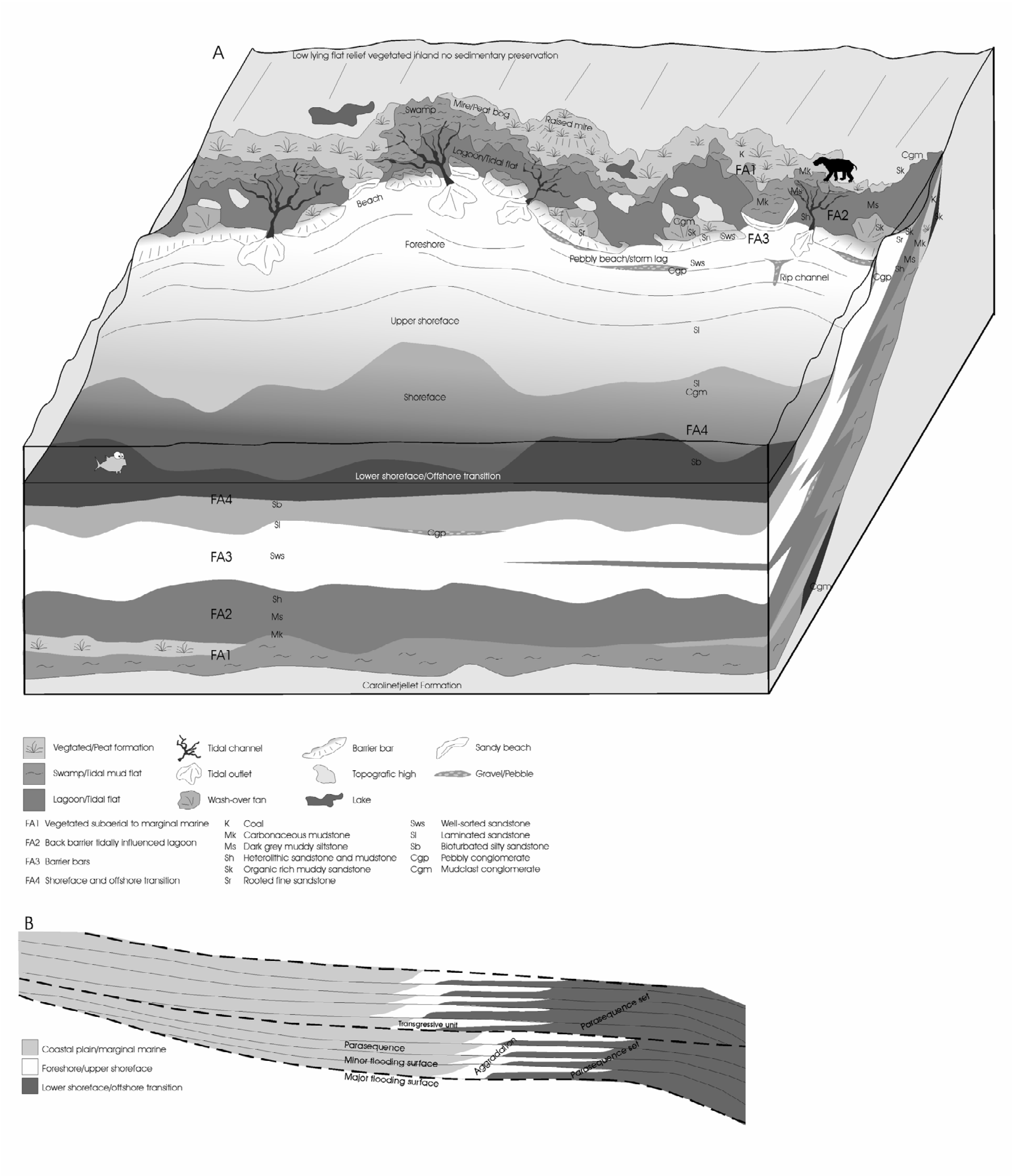

Fig. 3.1 (A) Conceptual diagram of the depositional environment and the distribution of facies and facies associations in the Firkanten Formation, after (Lüthje and Nichols, Submitted a; Appendix 4.2). (B) Conceptual diagram of the sequence stratigraphic model. The parasequences are minor prograding sections bounded by flooding surfaces. They build up parasequence sets bounded by major flooding surfaces. The parasequence sets sometimes have a transgressive lower unit and a dominant aggrading upper section, from (Lüthje and Nichols, Submitted b).

environmental zones, the facies associations; the vegetated subaerial to marginal marine, back barrier tidally influenced lagoon, barrier bars and foreshore, shoreface and offshore transition (Lüthje and Nichols, Submitted a).

Coastal plain

The costal plain was characterised by muddy deposits often with high organic content. The tidal reworking of the sediments indicates that large areas were influenced by tides. However, the typical tidal structures indicated a low energy regime since no signs of macrotidal impact were found, such as large tidal channels. This implies a low gradient coast where even a small tidal range would have impact on a large area.

On the coastal plain, large peat mires developed into raised mire complexes, forming the thick coal layers. These coal layers are mined in several places on Svalbard today where the larger coal seams are up to 5 metres thick. Considering the compaction of peat to coal this suggest that several tens of metres of peat accumulated in the mires. Single continuous mires could have a diameter of more than 5 km. The mire complexes extended within a zone from the coast towards the inland with a width of approximately 10 km. The great extent of the mire complexes confirms a low gradient. In this environment there are found tracks of Pantodonts, a large omnivore/herbivore mammal that is previously only known from the Paleocene of Northern America (Lüthje et al., Submitted). The dense vegetation must have been attractive to grazing animals.

The thick coal layers developed when the vegetation growth was in pace with relative sea level rise (creation of accommodation space) for a longer period indicating long term stable conditions. The eastern side of the basin tends to show thicker coal sections than in the west. Close to the thrust front the subsidence and the clastic sediment input was higher, which is normal for flexural basins (Fig. 2.12), limiting the coal accumulation resulting in thin and divided coal seams. The most favourable area for coal formation seems to have been on the eastern margin of the basin.

The mires developed into raised mires that occasionally acted as natural dikes for the marine transgression, which increased the thickness of the coal layer further. The coal is mostly ombrotrophic coal indicating that it was formed in mires or peat bogs. Occasionally sapropelic coal is found as thin layers on top of the coal seams indicating that the mires were flooded, transforming the mire into swamps, probably by raised ground water table preceding the marine transgression. Muddy coal and carbonaceous tidally influenced mudstone adjacent to coal layers were found in association to the marine transgression, indicating that the mires developed close to the marine realm on the coastal plain.

Back barrier

The muddy tidally influenced sediments were deposited as broad shallow marine lagoon and tidal flat complexes, characterised by organic-rich heterolithic mud and sandstone with mud drapes and herringbone structures. Microtidal influence on clastic deposits is diagnostic in the Todalen Member with no apparent specific variation over the basin or in time. These sediments were bioturbated and trace fossils found are *Planolites*, *Teredolites*, but also larger non-specified sand-filled ones. *Teredolites* are formed by marine bivalves that burrow down into flooded organic material. Surprisingly few macrofossils of marine shells or carbonate microfossils like foraminifers are found in the deposits (Nagy, 2005). In thin sections, carbonates are almost absent indicating that the carbonate might have been dissolved. The coastal mires could have generated acids that influenced the deposits through the ground water. With high yearly precipitation this can affect large areas outside the mire and also the nearby marine realm (McCabe, 1984).

At the base of the Todalen Member there is often found a mudclasts conglomerate in association with unsorted organic-rich sandstone. This is interpreted as the initial marine flooding of vegetated and weathered areas. The character of the sediment shows that it was dumped quickly with no depositional structures. Roots and, possible but not identified, continental trace fossils are occasionally associated with these layers indicating subaerial exposure. The basal unconformity is not isochronal. The flooding and initiation of sedimentation in new areas took place in steps during the major flooding events. The mudclasts were probably generated from the underlying Carolinefjellet Formation. The sequence stratigraphic correlation indicates an inherited relief in the underlying unconformity of less than twenty metres. Highs were left as local areas of non deposition on the coastal plain. However, the relief was filled in during the first stage of deposition (Lüthje and Nichols, Submitted b) and by the time the retrogradation progressed as far as the foreshore, all relief was filled in (Fig. 3.2).

The Danish Wadden Sea was put forward as a modern analogue for the Todalen Member. There are several similar characteristics such as; a low relief broad coastal plain, a peat forming environment, a transgressive coast, a mircotidal regime, and an extensive area of lagoon and tidal flat complexes protected by sandy barrier bars (Figs 3.3A and B). There are found no evidence of any large fluvial system in the Todalen Member. The sequence stratigraphy reveals an overall transgressive back-stepping environment, not symptomatic for delta systems. The general shape of the strata is very flat with no incisions. The fluvial input to the Todalen Member was probably restricted to the western side of the basin where the highest rate of subsidence was found close to the thrust front. Any fluvial drainage system

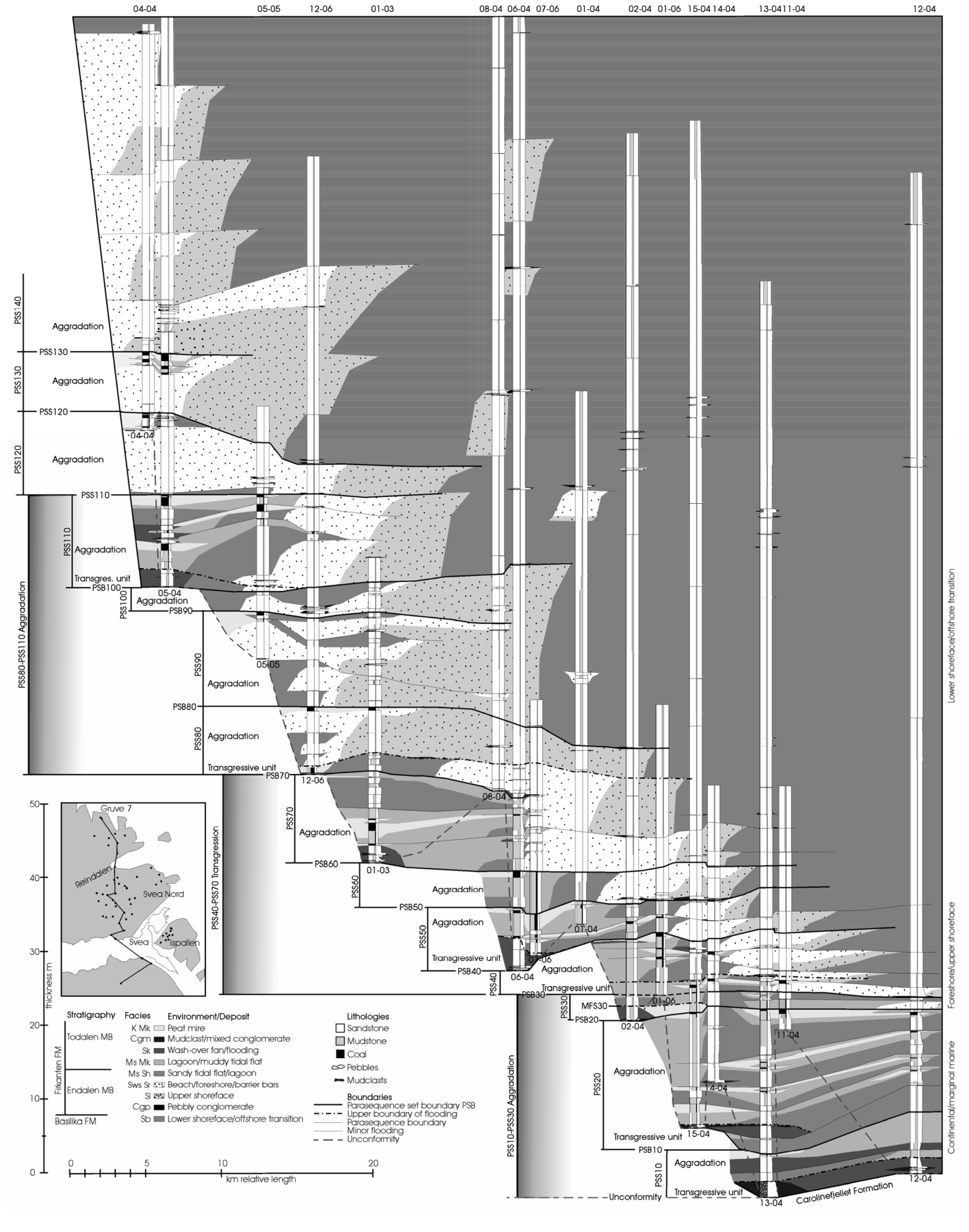

Fig. 3.2 Correlation panel of the Firkanten Formation from the eastern side of basin from south of Svea to Reindalen to Longyearbyen, from (Lüthje and Nichols, Submitted b; Appendix 4.3).

would naturally follow the depressions and areas of greatest subsidence. The configuration of the fine grained organic-rich rich deposits indicates a broad flat environment interpreted as coastal plain rather than delta plain. The presence of lagoons and tidal flats in a retrograding succession also indicate costal plain environment. The tidal deposits are not likely to have been generated as estuaries since there was no initial valley incision. The coal layers are

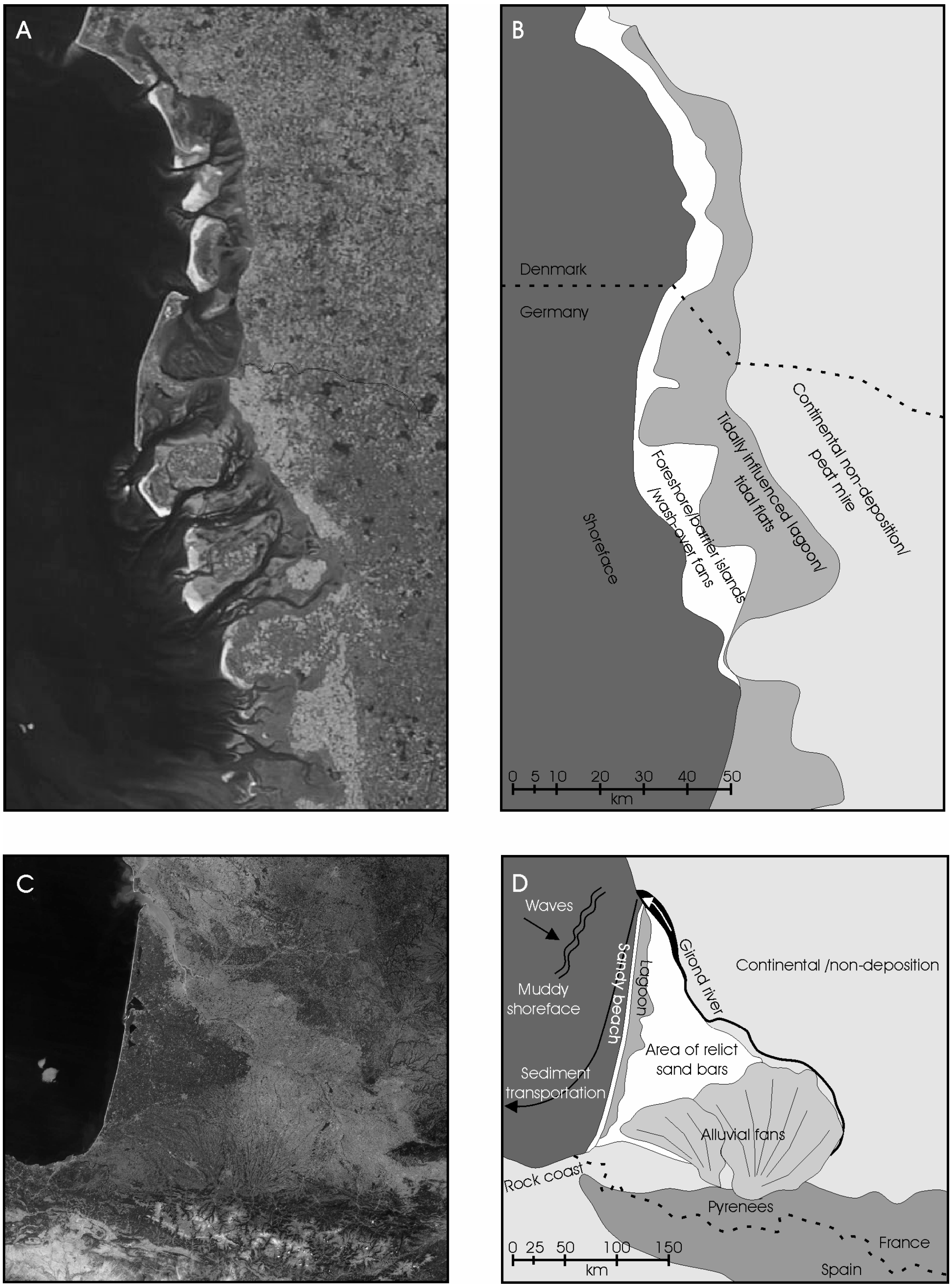

Fig. 3.3 Modern analogues (A) Satellite image of the Danish Wadden Sea, a modern analogue for the depositional environment in the Firkanten Formation (MODIS image from NASA Visible Earth, http://visibleearth.nasa.gov). (B) The coast is characterised by a wide tidally influenced lagoon and tidal flat areas protected from wave action by barrier bars/islands with well sorted foreshore sand deposition, from (Lüthje and Nichols, Submitted a). (C) Satellite image of the Bay of Biscay, a modern analogue for the sediment transportation in the Firkanten Formation (MODIS image from NASA Visible Earth, http://visibleearth.nasa.gov). (D) The coast is characterised by longshore current transportation. Fine grained sandstone is deposited in a narrow zone on the foreshore. The shoreface is muddy with glauconite production, from (Lüthje and Nichols, Submitted b).

extensive and thick, neither indicative for fluvial plain deposits since the clastic input would be expected to be too large to generate extensive peat deposits. A paleogeographic reconstruction of the depositional environment of Firkanten Formation is presented in Figure 3.4 (Appendix 4.4).

Foreshore, shoreface, and offshore transition

The coastal plain was protected from waves and storms by barrier bars and islands represented by the Endalen Member well sorted sandstone. The shoreface deposits are characterised by large scale hummocky cross-stratification, bioturbated during periods of quiescence. Typical trace fossils are *Ophiomorpha* and *Thalassinoides* (Lüthje and Nichols, Submitted a). The lower shoreface and the offshore transition is characterised by muddy intensely bioturbated sandstone. There is a wide range of trace fossils among which the following were identified *Ophiomorpha*, *Thalassinoides*, *Helminthopsis*, *Planolites*, *Paleophycus*, *Terebellina*, and *Teichichnus*.

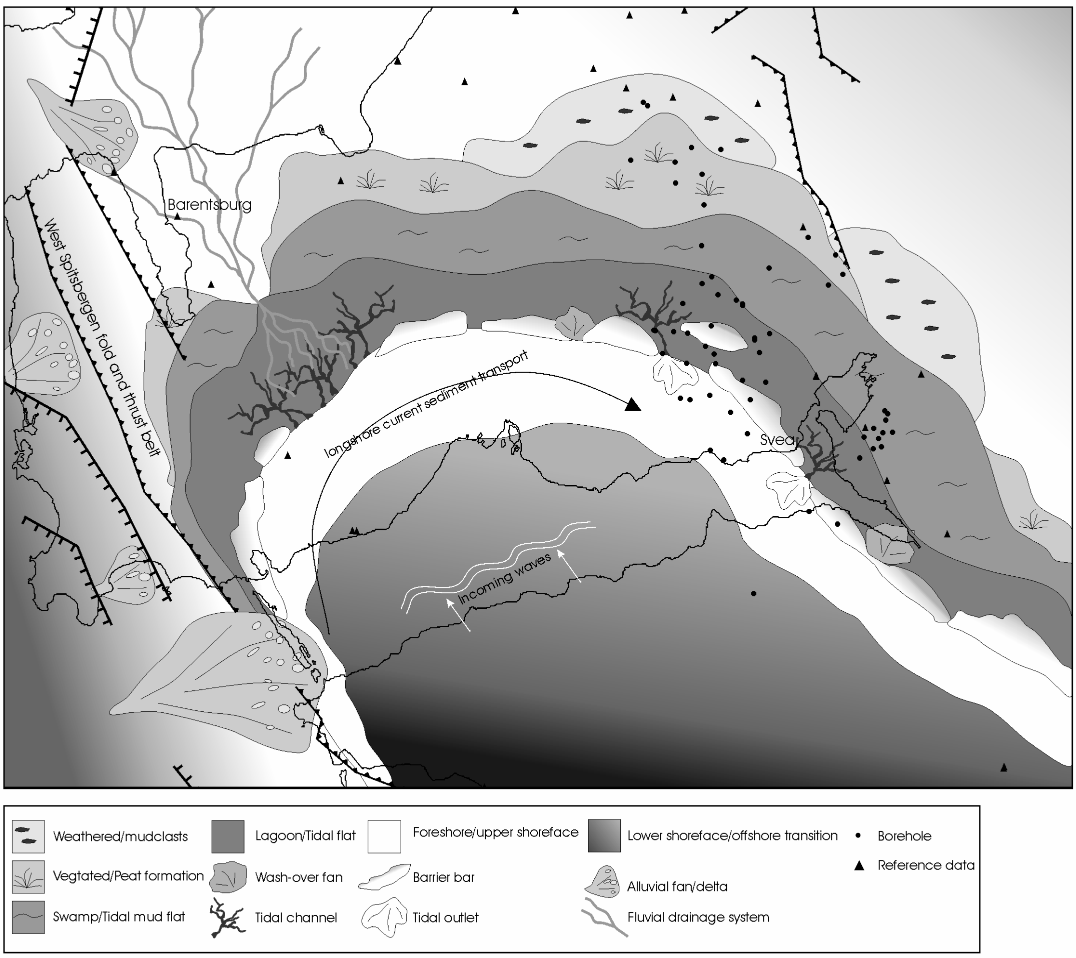

Fig. 3.4 Regional paleogeographic reconstruction of the Central Tertiary Basin showing sedimentary transportation pattern, fluvial drainage, and interpretation of the environmental setting, from (Lüthje and Nichols, Submitted b; Appendix 4.4).

The glauconite content of the sandstone indicates low sedimentation rate on parts of the shelf. The foreshore was relatively narrow and the well sorted fine grained sand was deposited from longshore wave and tidal induced currents (Lüthje and Nichols, Submitted b). The deposits were sourced from the west and the north where the most uplifted and eroded areas were situated (Nichols and Lüthje, Submitted). The sand entered the basin close to the thrust front. The French coast of Bay of Biscay has a similar sediment transportation character (Fig. 3.3C and D). Sediment input is restricted to the outlet of the Girond River to the north and is transported along the shore. The foreshore is characterised by fine grained sands in a narrow zone. The shoreface is muddy (even at a shallow water depth) and there is glauconite production. Similarly, the paleowater depth in the Endalen Member could therefore have been misinterpreted as deeper than the actual depth.

On the foreshore and the shoreface, pebbly layers deposited by storms were found. These pebbles were generated from the thrust belt to the west of the basin. The size of the pebbles in the fluvial deposits of the Grønfjorden Bed is much larger than found otherwise in the Firkanten Formation indicating sorting of the sediments along the coast. Occasionally, storms washed over the barrier bars and deposited wash-over fans of unsorted sediments and pebbly layers in the lagoons. The fluvial Grønfjorden Bed is only found locally in the west close to thrust front. It is interpreted to represent alluvial fans/deltas generated off the thrust front.

Aeolian dunes have not been identified in the succession. They may be expected in a regressive succession where sand deposited on the foreshore and shoreface would have been exposed for re-depositing by wind during sea level fall similar to the Bay of Biscay. Occasionally, the barrier bars in the Firkanten Formation are rooted especially when overlain by coal but otherwise the succession is overall transgressive/aggrading.

3.2 Basin configuration and development

The Central Tertiary Basin was structurally limited to the west by the fold and thrust belt, to the north by uplift, and to the east by restricted accommodation space (Figs 1.1, 2.4 and 3.4). The basin formation was connected to the fold and thrust belt and formed as a depression in front of the thrust front by tectonic subsidence. The Firkanten Formation is overall transgressive, showing a gradual back-stepping coastline with no relative sea level falls. The subsidence was at all time larger than any eustatic sea level rise.

The conceptual model for the sequence stratigraphy is presented in Figure 3.1B. The section is built up of minor prograding parasequences that are stacked in a general aggrading trend.

The parasequences are bounded by minor flooding events. The parasequences are combined into parasequence sets, with an aggrading stacking pattern in a general retrograding succession, bounded by major flooding surfaces. The parasequence sets occasionally have a lower transgressive unit deposited during flooding.

The aggrading sections were deposited in periods when relative sea level rise (accumulation space created) were in pace with the sedimentation. The transgression and flooding of areas took place in steps when the relative sea level rise increased and outpaced the sedimentation. This probably reflected eustatic variations (Lüthje and Nichols, Submitted b). In the well-correlation the aggrading successions of parasequence sets and the overall general retrograding trends stand out clearly (Fig. 3.2). The detailed well-correlation from south of Svea to Longyearbyen indicate that the parasequence sets can be combined further into higher level order of aggrading and retrograding successions.

The lowermost section consists of tidally influenced aggrading coastal plain deposits. The infilling of any relief in the underlying unconformity is covered by this section. The seawards side of the shoreline was dominated by sandy beach and foreshore to shoreface deposits. During the aggrading periods extensive coastal plain deposits accumulated as well as thick shoreface successions. The major flooding surfaces that separate the parasequence sets show a large offset in depositional environment relocating the coastline several kilometres.

Uplift of the fold and thrust belt was prior to deposition of the Firkanten Formation since it is shown that the sediments were generated form older deposits, which must have been uplifted and exposed prior to erosion. Pebbles were generated from the thrust front and the sand was from the eroded Mesozoic strata in the north. The extensional model (Steel et al., 1981; Steel et al., 1985) does not give any mechanism for this uplift and therefore a compressional model for the generation of the basin is preferable (Bruhn and Steel, 2003) in accordance with the recognition of compressional structures (Braathen et al., 1995; Bergh et al., 1997; Braathen et al., 1999).

The Central Tertiary Basin formed as a depression in front of the thrust front. The mechanism has been considered to be better explained as compressional folding (Nichols and Lüthje, Submitted) than flexural loading as suggested previously (Bruhn and Steel, 2003). Vertical strata close to the thrust front at Festningen indicate that the basin is the down fold of the crust, rather than formed as a regular foreland basin in connection to loading from thrusting. If it was formed from general thrusting there would have been indications that the thrust belt moved considerably during deformation and more sign of thrusting in the basin. Even thick continental crust can be extensively folded by compressional folding (Zhang and Bott, 2000). The mountain range was probably not extensively elevated. The newly discovered presence of Pantodonts on Svalbard (Luthje et al., Submitted) also indicates a relatively low mountain belt since it could otherwise have limited migration from Northern America where they are known from in Paleocene. This is consistent with compressional folding rather than flexural loading since no great mountain belt is needed to create the depression. The initial basin fill of continental and shallow marine strata gradually becoming more marine is also in accordance with compressional folding.

The uplifted northern area and the western fold and thrust belt was the provenance of the sediments, and from this western entry point the sediments were transported eastwards in the basin by longshore currents (Fig. 3.4). The subsidence on the western side seems to have been larger than in the east, indicating an asymmetrical basin. The flexural origin of the basin also indicates that it would probably have been asymmetrical. The thinner and heterolithic coal seams that are found on the western side indicate a higher sediment influx. High sediment influx is also indicated by the fluvial/alluvial fan systems on this side, the Grønfjorden Bed (Fig. 3.4).

The basin was limited for sedimentation to the east, possibly by an uplifted foreland bulge or more probably an area of no subsidence, and therefore no creation of accommodation space. This hypothetical foreland bulge has previously been suggested as provenance for the Firkanten Formation (Bruhn and Steel, 2003). However, the forebulge alone cannot be considered responsible for all the sediments since uplift of a forebulge is less than one tenth of the subsidence in a foreland basin (Allen and Allen, 2005). Furthermore, there is not discovered any major uplift and erosion in the Lower Cretaceous succession to the east.

The relative sea level rise was probably controlled by a combination of several factors of which tectonic subsidence dominated. The basin subsidence was from compressional folding with an additional effect of flexural loading and isostacy when the basin started to fill with sediments. The smaller variations in relative sea level change were caused by eustacy (Lüthje and Nichols, Submitted b). The sediment supply to the basin seems to have been uniform during the Firkanten Formation since there is no change in depositional environment.

8. CONCLUSIONS

This chapter summarises the conclusions from the research. Answers to the questions raised to the old interpretation are addressed and the new understanding of the Firkanten Formation and the Central Tertiary Basin is emphasised. Limitations and suggested work for the future are also discussed.

The PhD research project was initiated to investigate the depositional environment of the Firkanten Formation and its implications to coal exploration. The new interpretation and understanding that came out of this project has given a more comprehensive picture of the formation of the Central Tertiary Basin.

A new depositional environment model was proposed for the entire Firkanten Formation together with a paleogeographic reconstruction. A sequence stratigraphic model for the first phase of sediment infill of the Central Tertiary Basin was formed in line with the depositional environment. The tectonic control on the basin was discussed from a basin formation perspective and a new compressional model for basin formation was put forward.

8.1 Summary of conclusions

These general conclusions were made from this work:

- The Firkanten and Basilika Formations were deposited in an overall transgressive wave and storm dominated shallow marine setting.
- The subsidence of the basin was controlled by flexural tectonic of the crust from compressional folding creating a depression in front of the thrust front.
- The stepwise retrogradation of the basin, with intervening aggradational successions, took place in periods of increased relative sea level rise, probably eustatically driven.
- The tectonic subsidence was at any time larger than the eustatic sea level fall and no relative sea level falls were detected.
- The basin was bound to the west by the thrust front, to the north by uplift and to the east by a structurally controlled area with restricted sedimentation.
- The pebbly sediments were generated from the fold and thrust belt in the west while the sand provenance was the eroded Mesozoic strata in the north; no indications of an easterly sediment source was found.

- The Late Paleocene Firkanten Formation sediments rest on the Lower Cretaceous Carolinefjellet Formation and a minor but important local relief found in the unconformity influenced the initial deposition.
- The coal and carbonaceous mudstone of the Todalen Member were deposited on the sheltered low relief coastal plain in mires and swamps which gradually extended into lagoons and tidal flats in a microtidal energy regime.
- The coastal plain was inhabited by the Late Paleocene mammal Pantodont *Titanoides*, previously known from Northern America indicating an open migration path without major seaways or elevated mountain belts.
- The asymmetry of the flexural basin is reflected in the deposits where the western area is influenced by higher subsidence rate and sediment supply resulting in thinner coal deposits.
- The fluvial input is suggested to have been minor and only influencing the sedimentation in the western part of the basin, shown by the pebbly fluvial/alluvial fan delta of the Grønfjorden Bed.
- The eastern part of the basin was favourable for peat accumulation due to low subsidence and clastic sediment supply, where raised mire complexes had time to develop.
- The raised mires acted as natural dykes for transgressions resulting in thick sections of peat accumulations.
- The protecting barrier bars were built up by fine grained sandstone from longshore currents transporting sediments from the west towards the east and the glauconite content indicate a low sedimentation rate in parts of the shelf.
- The lower shoreface was mud prone and partly heavily bioturbated.

8.2 Answers to questions to old interpretation

Some questions were raised regarding the earlier interpretation of the Firkanten Formation. These have been discussed both in Chapter 3 *Synopsis of articles* and in the different articles. A short summary of the answers is presented here:

1. Does the Todalen Member represent a fluvial delta system?

   No, the Todalen Member was deposited on a low relief coastal plain in a microtidal regime with tidally influenced lagoons and peat mires protected from the wave and storm dominated shore by barrier bars.
2. Why are the coal-layers thick and broad and why are there no extensive fluvial channel deposits in the sections?

The peat mires developed on a coastal plain without any significant fluvial input on the eastern side of the basin and raised mires acted as natural dykes for marine transgressions resulting in extensive thick aggradational coal deposits.

3. Were there estuaries in the Todalen Member?

   No, since there are not found any indications of relative sea level fall or fluvial systems it is unlikely that there was any valley incision and hence no estuaries, therefore the tidally influenced deposits represent tidal flats and lagoons.

4. How were the conglomeratic beds deposited and where were the pebbles generated?

   The pebbles were generated from the thrust belt and shed into the basin as alluvial fans/deltas, from where they were transported by longshore currents especially during storms and deposited on the foreshore and shoreface but also as wash-over fans in the lagoons.

5. If the Todalen Member does not represent a delta plain setting, then what do the Endalen Member and the Basilika Formation represent?

   The Todalen Member is better described as a coastal plain deposit and this implies that the Endalen Member is the sandy foreshore and upper shoreface and the Basilika Formation is the lower shoreface and offshore transition of a wave and storm dominated transgressive coast.

6. Where did the sediments in the Firkanten Formation come from?

   The sandstone is shown to be generated from eroded Mesozoic strata in the north of the Central Tertiary Basin, which shows extensive erosion, the pebbles were generated from the thrust belt.

7. How was the basin formation related to the thrust belt?

   The basin formed as a depression in front of the thrust front from compressional tectonic movements, probably as compressional folding rather than a classical foreland basin formed by flexural loading.

8. Could the peripheral bulge have been a source of sediments for the Firkanten Formation?

   No, since there is no evidence of significant uplift or erosion to the east and due to the limited size of the suggested foreland bulge, it is better described as an area with limited sedimentation/accommodation space that possibly was structurally controlled.

9. What type of depositional coastline is represented in the Firkanten Formation?

   The Firkanten Formation was a retrograding depositional coastline with a wave and storm dominated shore with barrier bars and an inland area of tidally influenced lagoons and tidal flats gradually extending into swamps and peat mires.

10. How did the Central Tertiary Basin form?

    The Central Tertiary Basin formed from tectonic compression in a strike slip regime from convergence between Svalbard and Greenland in connection with the opening of the Northern Atlantic.

8.3 Future research and limitations to this work

The aim of the PhD project was to create a comprehensive model of the formation of the Firkanten Formation. The work resulted in a new depositional environmental model and a better understanding of the formation of the basin and the sequence development. However, during this work additional questions were raised that could not be answered within the scope of this PhD. To follow up on these questions, the results of this project have been linked to other research projects.

(i) The Pantodont tracks in the coal on Svalbard prove a close contact to the North American continent. To get a better understanding of the regional concept of how Svalbard, Northern Greenland, and Ellesmere Island were connected during the rifting and opening of the Arctic Ocean and the Northern Atlantic more work is needed to implement the results from the PhD project with data from the other regions. This has been initiated as project with CASP (Cambridge Arctic Shelf Programme, www.casp.cam.ac.uk). The aim is to implement the regional understanding of Northern Greenland and Ellesmere Island with the results from Svalbard. In addition CASP possesses raw data in form of sedimentary logs and samples that previously have not been processed or interpreted, from the western side of the Central Tertiary Basin. These new data will be processed and interpreted using the methods, the facies model, and the sequence stratigraphic model developed during this PhD. One of the limitations to the PhD work was inadequate data from the southern and western part of the basin. This is partly due to limited field exposures of the Firkanten Formation in these areas. Therefore the data from CASP, which also contains cores from the western side, will be important.

(ii) As part of this work it would be interesting to look further into the provenance, including petrography of the sediments but also the burial and uplift of the basin, which would involve establishing the thermal history by the use of for example a detailed vitrinite reflectance study.

(iii) The Paleocene Ny Ålesund Subgroup, from the Ny Ålesund area in the northern part of Spitsbergen (Fig. 1.1) has been suggested to be linked to the Central Tertiary Basin on the basis of similarity of the sediments. It is not possible to establish a direct link since the strata from north of Barentsburg all the way to Ny Ålesund was eroded during Cenozoic glaciations. To try to establish whether the two basins were the same, a project has been initiated to look at the sedimentary signature of the Ny Ålesund subgroup. This work started in 2005 with a short field season in Ny Ålesund and will be finished after the field season 2008. The preliminary results of this project suggest that the two basins might have been connected.

(iv) The coal samples gathered from the 3 mines; Gruve 3, Gruve 7, and Svea Nord have not been analysed for maceral content due to lack of access to the necessary equipment. However, it has been shown possible to use a detailed maceral study of complete vertical sections of coal seams to establish the relative sea level variations that took place during the accumulation of the peat (Davies, 2004; Davies et al., 2005). This will give further vital information to the sequence stratigraphy and perhaps better pinpoint the correlation of seams. A project has been initiated in connection with Liverpool University to look at the maceral distribution of the coal seams from the Central Tertiary Basin. The maceral content of the coal could also give more information about the climate and possible climatic changes since the maceral reflects the environment in which it was accumulated. It is also possible that a detailed study of the coal might reveal more information on the age of the sediments, especially if the maceral trends can be linked to sequence stratigraphic changes or perhaps global sea level changes.

(v) Defining the age of the Firkanten Formation is problematic since the biostratigraphy has proved to be hard to evaluate due to the absence of calcareous microfossils and intense quartz cementation of the sediment. It could be interesting to look at the possibility to extract palynomorphs from the coal for dating. A possibility could be to look further into a combination of data from separate sources such as coal macerals, plant material, sediment, fossils, trace fossils, paleoecological reconstructions, and tectonic plate reconstructions to make a comprehensive model that could further define the age. Each of the analysis would give a time range and combined together it might result in a more specific definition of the age.

9. REFERENCES

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10. APPENDIX

The appendix found on the attached CD contains full scale images of some of the figures in the thesis and the articles in addition to some extra material such as pictures of cores and from field. There are also pdf versions of the article manuscripts in a larger layout format.

1. Facies
   1.1. Core pictures of the facies
   1.2. Field pictures of facies
   1.3. Facies tables (A3 word document and excel file)
2. Logs
   2.1. Borehole logs (1:50/1:200)
   2.2. Reference logs (redrawn 1:50)
   2.3. Legend
3. Picture gallery
   3.1. Photomicrograph
   3.2. Pictures from the mines and the core store
4. Figures in large scale
   4.1. Facies pictures from cores and field (Figs 4A and B in Article 1)
   4.2. Depositional environment model (Fig. 3 in Article 2)
   4.3. Correlation log panels (4; black and white/colour; Figs 6-9 in Article 2)
   4.4. Paleogeographic reconstructions (Figs 11-14 in Article 2)
5. Articles as pdf with double line spacing and figures at the end of the text
   5.1. Article 1: Lüthje, C. and Nichols, G. Submitted. Coal formation in a coastal plain setting, Paleocene, Spitsbergen, Arctic Norway. Sedimentology.
   5.2. Article 2: Lüthje, C. and Nichols, G. Submitted. Transgressive coastal plain to shallow marine development of the Paleocene strata of Spitsbergen, Arctic Norway. Journal of Sedimentary Research.
   5.3. Article 3: Nichols, G. and Lüthje, C. Submitted. Provenance and Flexural Basin Development: the Paleocene of the Central Tertiary Basin, Spitsbergen. Basin Research.
   5.4. Article 4: Lüthje, C., Milàn, J. and Hurum, J. Submitted. Paleocene tracks of the mammal Pantodont genus *Titanoides* in coal-bearing strata, Svalbard, Arctic Norway. Proceedings of the Royal Society B.
6. Thesis as pdf